A CORN STOVER SUPPLY LOGISTICS SYSTEM

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ABSTRACT. *We evaluated the economics, energy inputs, and greenhouse gas (GHG) emissions for a proposed "field to facility" corn stover logistics system. The system included collection and transport by round bales to local storages within 3.2 km (2 mile) of the field during the fall harvest period followed by processing at the local storage sites throughout the year using mobile units which converted the bales to bulk material by tub-grinding and roll-press compacting to 240 kg/m^3 (15 lb/ft^3) to achieve 22.7-t (25-ton) loads for truck delivery to an end user within a 48-km (30-mile) radius. The total cost and fossil energy consumption for delivering the bulk corn stover (15% moisture) to end users were \$81/t (\$74/ton) and 936 MJ/t, respectively. The total fossil energy consumption was equivalent to approximately 7% of the energy content of corn stover. The life-cycle GHG emission for heat and power applications was approximately 114 kg CO$_2$e/t at 15% moisture or 8 g CO$_2$e/MJ of dry matter including emissions for logistics and combustion, but excluding those associated with soil organic carbon (SOC) loss. Our estimates show that as a fuel for heat and power applications, corn stover reduced life-cycle GHG emissions by factors of approximately 8 and 14 compared to natural gas and coal, respectively.*

Keywords. *Corn stover, Economics, GHG emission, Logistics, Roll press compaction, Tub grinding.*

Users of biomass need a consistent supply throughout the year. However, in the Upper Midwest collection/harvesting of herbaceous biomass is limited to certain times of the year, usually late summer or fall. A system is needed to collect, store, accumulate, process, densify (briquette or pellet), and deliver consistent, dense, free-flowing material to the users throughout the year. Collection/harvesting occurs on an agricultural cycle (late summer or fall time frame) while the use of biomass occurs on an industrial cycle which requires a continuous supply throughout the year. A key component requiring new approaches is the step involving accumulation of biomass stored at numerous field or farm sites and delivery to a processing facility or end user throughout the year in a form that is easy to handle and efficient to transport.

There have been several logistics systems proposed to transport biomass from the field to a conversion facility. Transport of baled (round or rectangular) biomass or ground/chopped biomass has been studied by several researchers (Sokhansanj et al., 2006a and 2006b; Wright et al., 2006; Brechbill and Tyner, 2008; Cundiff and Grisso, 2008; Petrolia, 2008). In addition to the high cost of transportation per unit mass of biomass delivered, handling baled or ground/chopped biomass materials would be difficult due to their low bulk densities. Most logistics studies involving bales or ground/chopped biomass have suggested increasing the bulk density of biomass to reduce the transportation cost and improve the handling of biomass (Jenkins et al., 1984; Mukunda et al., 2006; Sokhansanj and Fenton, 2006; Hess et al., 2007; Petrolia, 2008). Biomass materials can be densified into cubes, pellets, or briquettes using current technologies; however, the added cost of densification makes the feedstock more expensive (Sokhansanj and Turhollow, 2004; Sokhansanj et al., 2009).

The objective of this article is to evaluate economic, fossil energy, and greenhouse gas (GHG) emission impacts of a corn stover logistics system including: 1) collection and delivery to local storages within 3.2 km (2 mile) of the field in the fall, and 2) bale to bulk processing at the local storages followed by truck transport to a large end user within a 48-km (30-mile) radius throughout the year.

THE PROPOSED SYSTEM

We will summarize the proposed system and then discuss each component in more detail in following sections. Collection/harvesting of corn stover occurs after harvest of the corn grain. It involves stalk shredding to increase the amount of harvestable stover and to facilitate drying to the target moisture content of 15%. The stover is then raked, baled (round), and transported to local storages within 3.2 km (2 mile) of the field in the fall. Drawing stover from a 3.2-km (2-mile) radius for local storage is intended to strike a balance between the distance to move bales from the field at harvest and the desire to accumulate sufficient biomass [at least 181 t (200 ton)] for a minimum of one full day of bale to bulk processing at each site.

Baled material is processed at the local storages throughout the year and transported to an end user. The concept is to convert the bales to a bulk material with a density of at least 240 kg/m^3 (15 lb/ft^3) to allow for transport by trucks that will load out based on maximum weight [22.7 t

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(25 ton)] rather than volume. Bales are chopped or coarsely ground. The ground material is then compacted and loaded on trucks for delivery as a bulk product to the user. Kaliyan et al. (2009) evaluated a tub-grinding/roll-press compaction process to increase biomass bulk density to 240 kg/m^3 (15 lb/ft^3). Converting to a bulk form of biomass has additional advantages: 1) it eliminates potential problems associated with transporting bales that have lost their shape or structure because they have been in storage for a period of time, 2) material is easier to receive and handle for the end user, and 3) partial grinding or size reduction reduces the amount of processing required for further use.

The motivation for the logistics system is to provide biomass to meet the heat and power needs of a large scale user such as a corn ethanol plant. A 190 million L (50 million gal) per year ethanol plant would require around 450 t (500 ton) per day of corn stover to meet heat and power needs (De Kam et al., 2009; Tiffany et al., 2009). We believe this type of logistics system is applicable to many areas of the western corn belt in the United States, e.g., Southern Minnesota, Iowa, South Dakota, and Nebraska.

Performance measures including cost, life-cycle fossil energy input, and life-cycle GHG emission per tonne of biomass delivered to the end user are calculated with an Excel spreadsheet. The life-cycle GHG emissions related to the various logistics operations are calculated using the GHG emission metric "kg of CO_2 equivalent per tonne of corn stover (kg CO_2e/t)." The GHG emission metric of kg of CO_2 equivalent per tonne of corn stover is calculated by using the 100-year global warming potential (GWP) factors of 1 kg CO_2e/kg CO_2, 25 kg CO_2e/kg CH_4, and 298 kg CO_2e/kg N_2O (IPCC, 2007): kg CO_2e/t = [kg CO_2 + (25 × kg CH_4) + (298 × kg N_2O)]/t. In this study, we ignored the energy and GHG emission impacts related to the manufacturing and disposal of farm machinery, vehicles, and other equipment. The documentation of GHG emissions are expected to become increasingly important for businesses as international treaties and federal policies such as cap and trade are implemented.

COLLECTION AND TRANSPORT TO LOCAL STORAGE

The corn stover collection process includes shredding to increase the amount of harvestable stover and to facilitate drying to the target moisture content of 15% followed by raking, and round baling [567-kg (1250-lb) bales] after harvest of the corn grain in the fall. Bales are then moved to a local storage within 3.2 km (2 mile) of the field. This process typically occurs in a 4 to 6 week period from October to mid-November in the study region. Finding suitable time periods for shredding, raking, and round baling corn stover (15% moisture) is a critical step in the collection process.

Assumptions made for corn and stover yields, corn stover collection as round-bales, and the storage of bales at local storage sites are given in table 1. We assumed 70% corn stover removal per unit land area with collection every other year that corn is grown resulting in an average removal rate of 35% per year. This leads to more efficient, less costly collection with less compaction than harvesting 35% of the stover each year. System components and capacities, costs, fuel/energy use, and GHG emissions related to various field operations are summarized in table 2. System specifications are based on suggestions from a custom harvester who has successfully baled (average 15% moisture) and transported large volumes of corn stover to local storages over multiple years in Southern Minnesota using up to six balers and two bale movers (Woodford, 2008; Austin, 2009).

Table 1. Assumptions/variables used for corn stover collection/transport to local storage.

Assumptions/Variables	Value
Corn grain yield (#2 yellow corn) at 15.5% moisture (wet basis)	12.6 t/ha (200 bushels/acre)
Yield of stover as fraction of corn grain, dry matter/dry matter	1
Corn stover moisture in round bales	15% (wet basis)
Corn stover removed at 70% of above ground mass per unit land area (removal every other corn year; average removal of 35% per year)	7.4 t dry matter/ha (3.3 ton dry matter/acre) [8.7 t/ha (3.9 ton/acre)]
Weight of round bales [four wraps of HDPE net-wrap per bale of 1.8 m (6 ft) diameter × 1.5 m (5 ft) long]	567 kg (1250 lb)/bale (wet basis)
Average round-trip distance from field to local bale storage site	5.6 km (3.47 mile) [i.e., average round trip hauling distance in a 3.2-km (2-mile) radius with a winding factor of 1.3]

NUTRIENT REPLACEMENT AND SOIL ORGANIC CARBON

We considered nutrient replacement for the material removed from the field. Nutrient replacement estimates from various sources are summarized in table 3, along with values we chose for this study. Table 4 provides cost, life-cycle energy, and life-cycle GHG emissions for the nutrient replacement.

Soil organic carbon (SOC) reductions have implications for sustainability of the production process as well as contributing to greenhouse gas emissions as SOC stored in the soil decreases. Some research suggests that the SOC changes could be significant, but there is no agreement in the literature (Lal et al., 2004; Spatari et al., 2005; Sawyer and Mallarino, 2007a; Anderson-Teixeira et al., 2009).

Wilhelm et al. (2007) estimate allowable levels of corn stover removable to sustain SOC. At a grain yield of 12.6 t/ha (200 bushels/acre) under continuous corn and no or conservation tillage, they estimate that 30% to 35% of stover could sustainably be removed. Lower levels of removal would be required to sustain SOC for cases with lower yields, moldboard plowing, or corn-soybean rotations (Wilhelm et al., 2007). In this study, we did not quantify SOC changes from stover removal, but the system is based on sustainable removal rates of an average of 35% per year.

PAYMENT TO FARMER/LANDOWNER

Payment to the farmer is assumed to be $7.50/t ($6.80/ton) at 15% (w.b.) moisture content in addition to the payment for nutrient replacement.

LOCAL STORAGE

The round, net-wrapped bales are assumed to be stored uncovered at the local storage sites; thus, no storage structure is involved. The bales are assumed to be stored on a level surface in a line running north-south with the ends (diameter) butted tightly together with no obstructions to shade the bales, and the spacing between rows is 0.9 m (3 ft)

Table 2. Collection and local storage of corn stover by a farmer/custom operator.[a]

Operation	Tractor/ Power Unit Size, kW (hp)	Machine Capacity	Fuel Diesel Use, L/t (gal/ton)[b]	Lubricant Oil Use, L/t (gal/ton)[c]	Cost, \$/t (\$/ton)[d]	Life-Cycle Energy, MJ/t[e]	Life-Cycle GHG Emission, kg CO_2e/t[f]
Stalk shredding, 6 m (20 ft) width[g]	97 (130)	3.2 ha/h (7.8 acre/h)	0.789 (0.189)	0.005 (0.0011)	\$2.54 (\$2.30)	34.02	2.59
Raking, 9 m (30 ft) width[h]	78 (105)	10.6 ha/h (26.2 acre/h)	0.189 (0.045)	0.001 (0.0003)	\$1.54 (\$1.40)	8.15	0.62
Baling, large round bales[i]	119 (160)	3.8 ha/h (9.5 acre/h)	0.798 (0.191)	0.004 (0.0011)	\$21.16 (\$19.20)	34.38	2.62
Bale moving from field to storage site[j]	149 (200)	17.7 t/h (19.5 ton/h)	1.503 (0.360)	0.008 (0.0020)	\$5.51 (\$5.00)	64.76	4.93
Total	–	–	3.279 (0.786)	0.019 (0.0044)	\$30.75 (\$27.90)	196.89[k]	13.13[k]

[a] Mass or weight is defined at 15% (wet basis) moisture content unless otherwise indicated.

[b] Diesel consumption was assumed to be 0.223 L of diesel per PTO kW per h (0.044 gal of diesel per PTO hp-h) on average for each implement type (Lazarus, 2008).

[c] Oil consumption was estimated according to *ASABE Standards* (2009).

[d] Average custom rate cost data given by Edwards and Smith (2008) and Woodford (2008).

[e] Life-cycle energy (MJ/t) = [gal of diesel plus oil (i.e., fossil fuel)/ton of corn stover × 135.89 MJ/gal of fossil fuel] / [0.9072 × fossil fuel efficiency]. GREET (2009) provides a fossil fuel efficiency of 0.8377 to account for upstream energy consumption for fossil fuel production and distribution.

[f] Life-cycle GHG emission (kg CO_2e/t) = [gal of diesel plus oil (i.e., fossil fuel)/ton of corn stover × 135.89 MJ/gal of fossil fuel × 0.0909 kg CO_2e/MJ of fossil fuel] / 0.9072. GREET (2009) suggests an upstream (i.e., fuel production and distribution) emission factor and combustion emission factor of 17.23 and 73.64 g CO_2e/MJ of diesel fuel, respectively, for farm tractors.

[g] For example, John Deere 120 Drawn Flail Shredder, www.deere.com.

[h] For example, John Deere 705 Twin Rake, www.deere.com.

[i] For example, Vermeer 605 SUPER M Cornstalk Special Baler, www.vermeerag.com. The baling cost includes the cost of net-wrap at four wraps per bale which is \$2.59/bale or \$4.56/t (\$4.14/ton).

[j] For example, Highline Bale Mover 1400, www.highlinemfg.com. The capacity of the bale mover was calculated based on an average round-trip distance of 3.47 mile (5.6 km), an average tractor speed of 14 mile/h (22.5 km/h), 14 bales per round-trip, 7 min of total bale-loading time, and 5 min of total bale-unloading time based on a custom operator's experience (Woodford, 2008). The 14 bales on the bale mover are positioned in two rows of 7 each, end to end, which allows for rapid unloading in parallel rows at the local storage.

[k] Total includes 55.59 MJ/t and 2.37 kg CO_2e/t for life-cycle energy and GHG emission, respectively, for bale net-wrap [0.73 kg of net-wrap/t of corn stover (1.47 lb/ton)] made from HDPE (Pilz et al., 2005).

Table 3. Summary of nutrients replaced for corn stover.

Source	Nitrogen, kg/t dry matter (lb/ton dry matter)	Phosphorus (P_2O_5), kg/t dry matter (lb/ton dry matter)	Potassium (K_2O), kg/t dry matter (lb/ton dry matter)
Sheehan et al. (2004)	8.8 (17.6)	0.6 (1.2)	7.2 (14.4)
Spatari et al. (2005)	7.5 (15.0)	2.9 (5.8)	12.5 (25.0)
Sawyer and Mallarino (2007b)[a]	7.4 (14.8)	2.9 (5.9)	12.7 (25.4)
Brechbill and Tyner (2008)	7.9 (15.9)	2.9 (5.9)	15.0 (30.0)
Petrolia (2008)	0.0 (0.0)	3.1 (6.2)	16.5 (33.0)

[a] Nutrient replacement values used in our study.

(Shinners et al., 2007; Nickel, 2008). The storage cost estimate is based on the land required for storage plus the average loss during storage. The bale storage cost was estimated at 36¢/t (33¢/ton) assuming a land rent charge of \$494/ha (\$200/acre).

Shinners et al. (2007) reported that net-wrapped round bales [1.17 m (3.8 ft) width × 1.52 m (5.0 ft) diameter] of corn stover resulted in an average of 10% dry matter loss after 7 to 8 months (October/November to June) of outdoor storage in Arlington, Wisconsin. The bales were covered with 2.5 layers of to-edge net wrap. The initial moisture content of the corn stover was about 20% (w.b.) and the final moisture content at the end of storage was about 39% (w.b.). Richey et al. (1982) found that the dry matter loss of corn stover [1.7 m (5.6 ft) width × 1.7 m (5.6 ft) diameter round bales with 12 wraps of twine] stored outdoors for 7 months increased from 10% to 23% when the initial moisture content of the corn stover increased from 14% to 33% (w.b.).

In this analysis, the storage period ranged from 1 to 11 months. Also, since the corn stover bales were assumed to be collected at 15% (w.b.) moisture content and covered with four layers of net-wrap, we assumed an average storage loss of 5% for the range of storage periods. A storage loss of 5% means that 5% more corn stover is delivered to storage than is removed. Thus, an amount equal to 5% of the total for all categories (collection, nutrient replacement, payment to farmer) that occur prior to local storage is added to account for storage loss when calculating the total cost, energy input, and GHG emissions per unit of material delivered to the end user.

We believe this system will work for bales that are stored into early spring, but greater losses may be expected for bales that are going to be stored until late spring and summer. If losses become too large it may be necessary to introduce some type of covered storage to reduce losses of bales scheduled to be processed for delivery to the user in late spring and summer. We have not factored covered storage into the analysis at this point. Covered storage systems will likely be implemented when the cost of the losses exceeds the cost of some type of effective cover.

BALE TO BULK PROCESSING AT THE LOCAL STORAGE

Processing will occur throughout the year with mobile units moving from site to site. We assumed 1800 hours of processing per year, which would average about 36 hours per week over 50 weeks. We expect crews would work 8 to

Table 4. Nutrient replacement for corn stover removal.[a]

Nutrient/Emission Source	Fertilizer Used	Price per Unit Mass of Fertilizer, \$/t (\$/ton)[b]	Price per Unit Mass of Nutrient, \$/kg (\$/lb)	Mass of Nutrient Replaced per Unit Mass of Corn Stover Removed, kg/t dry matter (lb/ton dry matter)	Cost, \$/t (\$/ton)	Life-Cycle Energy, MJ/t[c]	Life-Cycle GHG Emission, kg CO_2e/t[c]
Nitrogen	Anhydrous ammonia	\$479.51 (\$435.00)	\$0.60 (\$0.27)	7.4 (14.8)	\$3.68 (\$3.34)	283.12	16.44
Phosphorus (P_2O_5)	Diammonium phosphate	\$386.91 (\$351.00)	\$0.82 (\$0.37)	2.9 (5.9)	\$2.04 (\$1.85)	35.03	2.58
Potassium (K_2O)	Potash	\$752.88 (\$683.00)	\$1.26 (\$0.57)	12.7 (25.4)	\$13.55 (\$12.29)	94.59	7.33
N_2O emission from nitrogen fertilizer[d]	–	–	–	–	–	–	39.03
N_2O credit due to corn stover removal[e]	–	–	–	–	–	–	-34.33
Total	–	–	–	–	\$19.26 (\$17.47)	412.74	31.04

[a] Mass or weight is defined at 15% (wet basis) moisture content unless otherwise indicated.

[b] Quoted Fall 2009 Southwest Minnesota prices.

[c] The life-cycle energy for nitrogen, P_2O_5, and K_2O is 45.01, 13.97, and 8.76 MJ/kg of nutrient, respectively (GREET, 2009). The life-cycle GHG emission for nitrogen, P_2O_5, and K_2O is 2.61, 1.03, and 0.68 kg of CO_2e/kg of nutrient, respectively (GREET, 2009).

[d] Nitrogen in N_2O emitted as % of nitrogen in nitrogen-fertilizer = 1.325% (GREET, 2009).

[e] Nitrogen in N_2O avoided per unit of nitrogen in corn stover removed = -1.25% dry basis (GREET, 2009). The nitrogen content of corn stover = 0.69% dry basis (Morey et al., 2009).

10 hours per day requiring about 4 work days out of 7 to achieve the required hours of processing. Each local storage should contain at least 181 t (200 ton) [320 bales at 567 kg (1250 lb) each] to allow for a full day's operation at the site. We assume that the end user will have at least 1 to 2 weeks of storage to allow for short-term interruptions in processing at the local storages due to weather conditions.

A portable processing unit with a capacity of 22.7 t/h (25 ton/h) or 181 t/day (200 ton/day) involving tub-grinding, roll-press compaction to 240 kg/m^3 (15 lb/ft^3), and loading trucks [22.7 t (25 ton) each] is proposed. A tub-grinder is a portable device in which a hammer mill applies impact and cutting forces yielding a range of particle sizes depending on the screen sizes used for the grinding process (Arthur et al., 1982; Wright et al., 2006). A roll-press compactor has two counter-rotating rolls and a hopper above the rolls (Pietsch, 1991; Dec, 2002). The tub-ground material is fed to the rolls through the hopper. The tub-ground material is densified by compression between the rolls (Kaliyan et al., 2009).

Material flows directly from the tub-grinder to the roll-press compactor and then in to the semi-trailer. Important operating information and cost data for bale to bulk processing are summarized in table 5. In this study, the initial moisture content of corn stover is assumed to be 15% (w.b.) (table 1). According to Kaliyan et al. (2009), the roll press compactor would perform well in the moisture content range of 10% to 20% (w.b.).

TRUCK TRANSPORT TO THE END USER

Bulk compacted corn stover is transported by truck in 22.7-t (25-ton) loads to end users. We assumed that local storage sites for corn stover were uniformly distributed within a 48-km (30-mile) radius of the end user for the base case. The average straight line one-way hauling distance is 32 km (20 mile) (i.e., 2/3 of radius). The average round-trip hauling distance assuming a winding factor of 1.3 is 84 km (52 mile).

To reduce productivity losses of waiting for trucks, we assume the use of additional "drop trailers." In this way, tub-grinding and roll-press compacting can continue with space to load an additional trailer. When a truck returns to the remote site, an empty trailer is "dropped" and a trailer full of compacted biomass is hauled away. We assume that equipment is available to achieve high unloading rates at the end user. Also, the costs for materials handling and storage at the facility are the responsibility of the end user; thus, our analysis stops at the point of delivery to the facility. Cost, energy, and GHG emissions for truck transport are summarized in table 6.

HEAT AND POWER (COMBUSTION) APPLICATIONS

An important potential application of corn stover is to replace natural gas or coal to meet heat and power needs at large scale users such as ethanol plants. To compare corn stover as a replacement for these fossil fuels, the emissions associated with combustion are needed. Although as a biomass fuel, the CO_2 emissions are considered carbon neutral, methane (CH_4) and nitrous oxide (N_2O) emissions associated with the combustion must be considered. The CH_4 and N_2O emissions for corn stover combustion amount to 3.13 g CO_2e/MJ of dry matter (GREET, 2009).

RESULTS AND DISCUSSION

The total cost and life-cycle fossil energy consumption for corn stover logistics are \$81.29/t (\$73.75/ton) and 936 MJ/t, respectively (table 7). The life-cycle GHG emission for corn stover logistics and combustion is 114 kg CO_2e/t (table 7). The life-cycle GHG emission value does not include any contribution for reduction in soil organic carbon loss because of our restrictions on corn stover annual removal of 35%. While there is uncertainty related to allowable removal levels on particular soils, we believe our 35% removal assumption is reasonable.

Table 5. Bale to bulk processing of corn stover by an aggregator.[a]

Operation	Tractor/Power Unit Size, kW (hp)	Machine Capacity, t/h (ton/h)	Fuel Diesel Use, L/t (gal/ton)[b]	Lubricant Oil Use, L/t (gal/ton)[c]	Cost, \$/t (\$/ton)	Life-Cycle Energy, MJ/t [d]	Life-Cycle GHG Emission, kg CO_2e/t[e]
Feeding bales into tub-grinder with a tractor and front-end loader	97 (130)	22.7 (25)	0.477 (0.114)	0.006 (0.0013)	\$2.08 (\$1.89)	20.69	1.58
Tub grinding of bales[f]	403 (540)[g]	22.7 (25)	4.507 (1.080)[g]	0.020 (0.0048)	\$5.18 (\$4.70)	193.98	14.83
Roll-press compacting of tub-ground corn stover particles[h]	45 (60)[i]	22.7 (25)	0.441 (0.106)	0.003 (0.0007)	\$2.48 (\$2.25)	19.01	1.45
Payment to aggregator	–	–	–	–	\$3.75 (\$3.40)	–	–
Total	–	–	5.425 (1.300)	0.028 (0.0068)	\$13.49 (\$12.24)	233.68	17.85

[a] Mass or weight is defined at 15% (wet basis) moisture content unless otherwise indicated.

[b] Diesel consumption was assumed to be 0.223 L of diesel per PTO kW per hour (0.044 gal of diesel per PTO horsepower-hour) on average for each implement type (Lazarus, 2008).

[c] Oil consumption was estimated according to *ASABE Standards* (2009).

[d] Life-cycle energy (MJ/t) = [gal of diesel plus oil (i.e., fossil fuel)/ton of corn stover × 135.89 MJ/gal of fossil fuel] / [0.9072 × fossil fuel efficiency]. GREET (2009) provides a fossil fuel efficiency of 0.8377 to account for upstream energy consumption for fossil fuel production and distribution.

[e] Life-cycle GHG emission (kg CO_2e/t) = [gal of diesel plus oil (i.e., fossil fuel)/ton of corn stover × 135.89 MJ/gal of fossil fuel × 0.0913 kg CO_2e/MJ of fossil fuel] / 0.9072. GREET (2009) suggests an upstream (i.e., fuel production and distribution) emission factor and combustion emission factor of 17.23 and 74.02 g CO_2e/MJ of diesel fuel, respectively, for stationary reciprocating engines (tub-grinder and roll-press compactor). The GHG emission factors suggested for farm tractors were used to estimate the life-cycle GHG emission for the bale-feeding tractor (table 2; GREET, 2009).

[f] Fixed cost of tub-grinder equals \$2.43/t (\$2.20/ton) based on the following: first cost = \$390,000; salvage value = 10% of first cost; operating hours = 1800 h/year; life = 5 years; interest rate = 6%; and annual repair costs = 3% of first cost. The cost for insurance and housing is calculated based on procedures from Lazarus (2008).

[g] Data from Vermeer TG5000 tub-grinder (Vermeer Corporation, Pella, Iowa; www.vermeer.com).

[h] Fixed cost of roll-press compactor equals \$1.87/t (\$1.70/ton) based on the following: first cost = \$300,000; salvage value = 10% of first cost; operating hours = 1800 h/year; life = 5 years; interest rate = 6%; and annual repair costs = 3% of first cost. The cost for insurance and housing is calculated based on procedures from Lazarus (2008).

[i] Estimate based on roll-press design procedures given by Johanson (1965) and Dec (2002).

The four operations in the actual logistics process (collection/transport to local storage, local storage and loss, tub-grinding/roll-press compaction, and truck transport) comprise almost 67% of the total cost, approximately 56% of the life-cycle fossil energy input, but only about 33% of the life-cycle GHG emissions for heat and power applications. Over half (38% out of 67%) of the cost is attributed to the collection/transport to local storage step. This suggests that focusing on cost reduction, particularly for collection/transport to local storage, will be an important activity for these key operations in any logistics system.

Truck transport to the end user contributes 8.7%, 6.7%, and 4.2% to total cost, life-cycle fossil energy use, and life-cycle GHG emissions, respectively, for transport within a 48-km (30-mile) radius. Doubling the radius from 48 to 96 km (30 to 60 mile) increases total cost, life-cycle fossil energy use, and life-cycle GHG emissions by another 8.7%, 6.7%, and 4.2%, respectively, while increasing the area from which to draw corn stover by a factor of 4. Increasing the radius by a factor of 4 from 48 to 192 km (30 to 120 mile) would increase the area from which to draw corn stover by a factor of 16 while increasing total cost, life-cycle fossil energy use, and life-cycle GHG emissions by 26.0%, 20.1%, and 12.7%, respectively.

The lower heating value (LHV) of corn stover is 16.7 MJ/kg of dry matter (Morey et al., 2009). Thus, the total fossil energy consumption for nutrient replacement, collection, processing at the local storage, and transport to the end user is equivalent to approximately 6.6% of the energy content of the biomass. The total life-cycle GHG emission is 8.0 g CO_2e/MJ of dry matter including combustion.

Table 6. Truck transport of compacted corn stover to users.[a]

Operation	Power Unit	Truck Load, t (ton)	Fuel Diesel Use, L/t (gal/ton)	Lubricant Oil Use, L/t (gal/ton)	Cost, \$/t (\$/ton)[b]	Life-Cycle Energy, MJ/t[c]	Life-Cycle GHG Emission, kg CO_2e/t[d]
Trucking of compacted corn stover by semi-truck to users	Semi-truck with a diesel consumption of 0.018 L/t-km (0.007 gal/ton-mile)	22.7 (25)	1.447 (0.347)	0.009 (0.0021)	\$7.05 (\$6.40)	62.36	4.78
Total	–	–	1.447 (0.347)	0.009 (0.0021)	\$7.05 (\$6.40)	62.36	4.78

[a] Mass or weight is defined at 15% (wet basis) moisture content unless otherwise indicated.

[b] We assumed the cost of the dedicated semi-truck transport is \$800 per day. In a day, semi-truck can make five round-trips for a user located at 84 km (52 mile) per round-trip, totaling 418 km (260 mile) of driving per day.

[c] Life-cycle energy (MJ/t) = [gal of diesel plus oil (i.e., fossil fuel)/ton of corn stover × 135.89 MJ/gal of fossil fuel] / [0.9072 × fossil fuel efficiency]. GREET (2009) provides a fossil fuel efficiency of 0.8377 to account for upstream energy consumption for fossil fuel production and distribution.

[d] Life-cycle GHG emission (kg CO_2e/t) = [gal of diesel plus oil (i.e., fossil fuel)/ton of corn stover × 135.89 MJ/gal of fossil fuel × 0.0916 kg CO_2e/MJ of fossil fuel] / 0.9072. GREET (2009) suggests an upstream (i.e., fuel production and distribution) emission factor and combustion emission factor of 17.23 and 74.35 g CO_2e/MJ of diesel fuel, respectively, for heavy-duty trucks.

Table 7. Cost, life-cycle fossil energy consumption, and life-cycle GHG emission for corn stover.[a]

	Cost		Life-Cycle Energy		Life-Cycle GHG Emission	
Operation	\$/t (\$/ton)	%	MJ/t	%	kg CO$_2$e/t	%
Payment to farmer for participation	\$7.50 (\$6.80)	9.2	–	–	–	–
Nutrient replacement (N-P-K)	\$19.26 (\$17.47)	23.7	412.7	44.1	31.0	27.3
Collection/transport to local storage	\$30.75 (\$27.90)	37.8	196.9	21.0	13.1	11.6
Local storage cost/local storage loss[b]	\$3.24 (\$2.94)	4.0	30.5	3.3	2.2	1.9
Tub-grinding/roll-press compaction	\$13.49 (\$12.24)	16.6	233.7	25.0	17.9	15.7
Truck transport of compacted corn stover	\$7.05 (\$6.40)	8.7	62.4	6.7	4.8	4.2
Combustion of corn stover[c]	–	–	–	–	44.5	39.2
Total	\$81.29 (\$73.75)	100.0	936.2	100.0	113.5	100.0

[a] Mass or weight is defined at 15% (wet basis) moisture content unless otherwise indicated.

[b] Average dry matter loss during storage was assumed to be 5%. The cost due to the storage and storage loss is equal to the sum of 36¢/t (33¢/ton) for the land rent charge, plus 5% of the costs for payment to farmer for participation, nutrient replacement, and collection/transport to local storage. The energy or GHG emission due to storage loss is equal to the sum of 5% of the corresponding values for nutrient replacement, and collection/transport to local storage.

[c] Combustion of corn stover in industrial boilers emits 0.0036 g of CH$_4$/MJ and 0.0102 g of N$_2$O/MJ of dry matter (GREET, 2009).

The life-cycle GHG emissions for corn stover, natural gas, and coal as fuels for heat and power applications are compared in figure 1. These estimates show that for heat and power applications, corn stover reduces life-cycle fossil GHG emissions by factors of approximately 8 and 14 compared to natural gas and coal, respectively.

SUMMARY AND CONCLUSIONS

In this study, we modeled a corn stover logistics system that included collection and transport of corn stover (15% moisture) as net-wrapped round bales to local storages within 3.2 km (2 mile) of the field in the fall. This stage was followed by processing at the local storage sites throughout the year using mobile units which converted the bales to bulk material by tub-grinding and roll-press compacting to 240 kg/m^3 (15 lb/ft^3). Bulk compacted corn stover is then loaded on trucks and delivered as 22.7-t (25-ton) loads to an end user within a 48-km (30-mile) radius. Other components of the logistics system were payment to the farmer for participation, nutrient replacement, and local storage loss. For the assumptions made for the proposed corn stover logistics system, we found the following:

- Delivered cost is \$81/t (\$74/ton).
- Fossil energy input is about 7% of energy in corn stover.
- Life-cycle GHG emissions are about 114 kg of CO$_2$e/tonne including combustion, but excluding soil organic carbon loss.
- Collection/transport to local storage, local storage and loss, tub-grinding/roll-press compaction, and truck transport comprise almost 67% of the total cost, but only about 33% of the life-cycle GHG emissions.
- Truck transport within a 48-km (30-mile) radius of the end user contributes 8.7% to total cost, but only 4.2% to life-cycle GHG emissions.
- For heat and power applications, life-cycle GHG emissions for corn stover fuel are approximately 8 g CO$_2$e/MJ of dry matter, which amounts to an 8 or 14 times reduction in GHG emissions compared to natural gas or coal fuels, respectively.

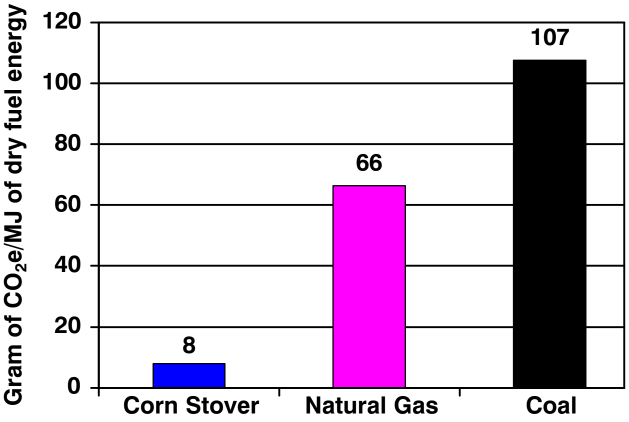

Figure 1. Life-cycle greenhouse gas emissions for heat and power applications. The GHG data for natural gas and coal include upstream (i.e., fuel production and distribution) and combustion emissions as fuels in industrial boilers (GREET, 2009).

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