A CORN STOVER SUPPLY LOGISTICS SYSTEM

R. V. Morey, N. Kaliyan, D. G. Tiffany, D. R. Schmidt

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/m³ (15 lb/ft³) 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 CO₂e/t at 15% moisture or 8 g CO₂e/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/m³ (15 lb/ft³) to allow for transport by trucks that will load out based on maximum weight [22.7 t
value 15% (wet basis)

emission metric "kg of CO₂ equivalent per tonne of corn

logistics operations are calculated using the GHG

life-cycle GHG emissions related to

biomass delivered to the end user are calculated with an

energy input, and life-cycle GHG emission per tonne of

corn belt in the United States, e.g., Southern Minnesota,

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 CO₂ equivalent per tonne of corn

stover (kg CO₂e/t).” The GHG emission metric of kg of CO₂

equivalent per tonne of corn stover is calculated by using the

100-year global warming potential (GWP) factors of 1 kg

CO₂e/kg CO₂, 25 kg CO₂e/kg CH₄, and 298 kg CO₂e/kg N₂O

(IPCC, 2007): kg CO₂e/t = [kg CO₂ + (25 × kg CH₄) +

(298 × kg N₂O)]/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).

**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)
et al. (1982) found that the dry matter loss of corn stover content at the end of storage was about 39% (w.b.). Richey et al. (2007) reported that net-wrapped round bales of corn stalk increased from 14% to 33% (w.b.) when the initial moisture content increased from 10% to 23% when the initial moisture content was 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.

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.

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

<table>
<thead>
<tr>
<th>Operation</th>
<th>Tractor/Power Unit Size, kw (hp)</th>
<th>Machine Capacity</th>
<th>Fuel Diesel Use, L/t (gal/ton)²</th>
<th>Lubricant Oil Use, L/t (gal/ton)³</th>
<th>Cost, $/t ($/ton)⁴</th>
<th>Life-Cycle Energy, MJ/²</th>
<th>Life-Cycle GHG Emission, kg CO₂e/t²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stalk shredding, 6 m (20 ft) width ¹</td>
<td>97 (130)</td>
<td>3.2 ha/h (7.8 acre/h)</td>
<td>0.789 (0.189)</td>
<td>0.005 (0.0011)</td>
<td>$2.54 ($2.30)</td>
<td>34.02</td>
<td>2.59</td>
</tr>
<tr>
<td>Raking, 9 m (30 ft) width¹</td>
<td>78 (105)</td>
<td>10.6 ha/h (26.2 acre/h)</td>
<td>0.189 (0.045)</td>
<td>0.001 (0.0003)</td>
<td>$1.54 ($1.40)</td>
<td>8.15</td>
<td>0.62</td>
</tr>
<tr>
<td>Baling, large round bales⁴</td>
<td>119 (160)</td>
<td>3.8 ha/h (9.5 acre/h)</td>
<td>0.798 (0.191)</td>
<td>0.004 (0.0011)</td>
<td>$21.16 ($19.20)</td>
<td>34.38</td>
<td>2.62</td>
</tr>
<tr>
<td>Bale moving from field to storage site⁴</td>
<td>149 (200)</td>
<td>17.7 t/h (19.5 ton/h)</td>
<td>1.503 (0.360)</td>
<td>0.008 (0.0020)</td>
<td>$5.51 ($5.00)</td>
<td>64.76</td>
<td>4.93</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>3.279 (0.786)</td>
<td>-</td>
<td>0.019 (0.0044)</td>
<td>$30.75 ($27.90)</td>
<td>196.89</td>
<td>13.13</td>
</tr>
</tbody>
</table>

¹ Mass or weight is defined at 15% (wet basis) moisture content unless otherwise indicated.
² 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).
⁴ Estimated fuel use based on a standard tractor, 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.
⁵ Total includes 55.59 MJ/t and 2.37 kg CO₂e/t for life-cycle energy and GHG emission, respectively, for farm tractors.

**Table 3. Summary of nutrients replaced for corn stover.**

<table>
<thead>
<tr>
<th>Source</th>
<th>Nitrogen (kg/t dry matter) (lb/ton dry matter)</th>
<th>Phosphorus (P₂O₅) (kg/t dry matter) (lb/ton dry matter)</th>
<th>Potassium (K₂O) (kg/t dry matter) (lb/ton dry matter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheehan et al. (2004)</td>
<td>8.8 (17.6)</td>
<td>0.6 (1.2)</td>
<td>7.2 (14.4)</td>
</tr>
<tr>
<td>Spatarì et al. (2005)</td>
<td>7.5 (15.0)</td>
<td>2.9 (5.8)</td>
<td>12.5 (25.0)</td>
</tr>
<tr>
<td>Sawyer and Mallarino (2007b)⁴</td>
<td>7.4 (14.8)</td>
<td>2.9 (5.9)</td>
<td>12.7 (25.4)</td>
</tr>
<tr>
<td>Brechbill and Tyner (2008)</td>
<td>7.9 (15.9)</td>
<td>2.9 (5.9)</td>
<td>15.0 (30.0)</td>
</tr>
<tr>
<td>Petrolia (2008)</td>
<td>0.0 (0.0)</td>
<td>3.1 (6.2)</td>
<td>16.5 (33.0)</td>
</tr>
</tbody>
</table>

⁴ 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 $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.).
Table 4. Nutrient replacement for corn stover removal.\[a]\n
| 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/lb\[c] | Life-Cycle GHG Emission, kg CO₂e/lb\[d]\n|------------------------|----------------|---------------------------------|---------------------------------|---------------------------------|----------------|----------------|----------------|
| Nitrogen               | Anhydrous ammonia | $479.51 ($435.00) | $0.60 ($0.27) | 7.4 (14.8) | $3.68 ($3.34) | 283.12 | 16.44 |
| Phosphorus (P₂O₅)      | Diammonium phosphate | $386.91 ($351.00) | $0.82 ($0.37) | 2.9 (5.9) | $2.04 ($1.85) | 35.03 | 2.58 |
| Potassium (K₂O)        | Potash        | $752.88 ($683.00) | $1.26 ($0.57) | 12.7 (25.4) | $13.55 ($12.29) | 94.59 | 7.33 |

\[a\] 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, P₂O₅, and K₂O is 45.01, 13.97, and 8.76 MJ/kg of nutrient, respectively (GREET, 2009). The life-cycle GHG emission for nitrogen, P₂O₅, and K₂O is 2.61, 1.03, and 0.68 kg of CO₂e/kg of nutrient, respectively (GREET, 2009).
\[d\] Nitrogen in N₂O avoided per unit of nitrogen in nitrogen-fertilizer = 1.325% (GREET, 2009).
\[e\] Nitrogen in N₂O 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/m³ (15 lb/ft³), 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.).

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 CO₂ emissions are considered carbon neutral, methane (CH₄) and nitrous oxide (N₂O) emissions associated with the combustion must be considered. The CH₄ and N₂O emissions for corn stover combustion amount to 3.13 g CO₂e/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 CO₂e/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.
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 (58% 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 CO₂e/MJ of dry matter including combustion.

### Table 5. Bale to bulk processing of corn stover by an aggregator

<table>
<thead>
<tr>
<th>Operation</th>
<th>Tractor/Power Unit Size, kW (hp)</th>
<th>Machine Capacity, t/h (ton/h)</th>
<th>Fuel Diesel Use, L/t (gal/ton)[b]</th>
<th>Lubricant Oil Use, L/t (gal/ton)[c]</th>
<th>Cost, $/t ($/ton)</th>
<th>Life-Cycle Energy, MJ/t [d]</th>
<th>Life-Cycle GHG Emission, kg CO₂e/t[e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeding bales into tub-grinder with a tractor and front-end loader</td>
<td>97 (130)</td>
<td>22.7 (25)</td>
<td>0.477 (0.114)</td>
<td>0.006 (0.0013)</td>
<td>$2.08 ($1.89)</td>
<td>20.69</td>
<td>1.58</td>
</tr>
<tr>
<td>Tub grinding of bales[fl]</td>
<td>403 (540)[f]</td>
<td>22.7 (25)</td>
<td>4.507 (1.080)[f]</td>
<td>0.020 (0.0048)</td>
<td>$5.18 ($4.70)</td>
<td>193.98</td>
<td>14.83</td>
</tr>
<tr>
<td>Roll-press compacting of tub-ground corn stover particles[fl]</td>
<td>45 (60)[fl]</td>
<td>22.7 (25)</td>
<td>0.441 (0.106)</td>
<td>0.003 (0.0007)</td>
<td>$2.48 ($2.25)</td>
<td>19.01</td>
<td>1.45</td>
</tr>
<tr>
<td>Payment to aggregator</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>-</td>
<td>5.425 (1.300)</td>
<td>0.028 (0.0068)</td>
<td>$13.49 ($12.24)</td>
<td>233.68</td>
<td>17.85</td>
</tr>
</tbody>
</table>

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

The 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.

The life-cycle GHG emission (kg CO₂e/t) = [gal of diesel plus oil (i.e., fossil fuel)/ton of corn stover × 135.89 MJ/gal of fossil fuel × 0.0913 kg CO₂/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 CO₂e/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).

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### Table 6. Truck transport of compacted corn stover to users

<table>
<thead>
<tr>
<th>Operation</th>
<th>Power Unit</th>
<th>Truck Load, t (ton)</th>
<th>Fuel Diesel Use, L/t (gal/ton)[c]</th>
<th>Lubricant Oil Use, L/t (gal/ton)[c]</th>
<th>Cost, $/t ($/ton)[c]</th>
<th>Life-Cycle Energy, MJ/t [d]</th>
<th>Life-Cycle GHG Emission, kg CO₂e/t[e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trucking of compacted corn stover by semi-truck to users</td>
<td>Semi-truck with a diesel consumption of 0.018 L/t-km (0.0007 gal/ton-mile)</td>
<td>22.7 (25)</td>
<td>1.447 (0.347)</td>
<td>0.009 (0.0021)</td>
<td>$7.05 ($6.40)</td>
<td>62.36</td>
<td>4.78</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>-</td>
<td>1.447 (0.347)</td>
<td>0.009 (0.0021)</td>
<td>$7.05 ($6.40)</td>
<td>62.36</td>
<td>4.78</td>
</tr>
</tbody>
</table>

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

The 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.

The life-cycle GHG emission (kg CO₂e/t) = [gal of diesel plus oil (i.e., fossil fuel)/ton of corn stover × 135.89 MJ/gal of fossil fuel × 0.0913 kg CO₂/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 CO₂e/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]

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cost</th>
<th>Life-Cycle Energy</th>
<th>Life-Cycle GHG Emission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$/t ($/ton)</td>
<td>%</td>
<td>MJ/t</td>
</tr>
<tr>
<td>Payment to farmer for participation</td>
<td>$7.50 ($6.80)</td>
<td>9.2</td>
<td>-</td>
</tr>
<tr>
<td>Nutrient replacement (N-P-K)</td>
<td>$19.26 ($17.47)</td>
<td>23.7</td>
<td>412.7</td>
</tr>
<tr>
<td>Collection/transport to local storage</td>
<td>$30.75 ($27.90)</td>
<td>37.8</td>
<td>196.9</td>
</tr>
<tr>
<td>Local storage cost/local storage loss[^b]</td>
<td>$3.24 ($2.94)</td>
<td>4.0</td>
<td>30.5</td>
</tr>
<tr>
<td>Tub-grinding/roll-press compaction</td>
<td>$13.49 ($12.24)</td>
<td>16.6</td>
<td>233.7</td>
</tr>
<tr>
<td>Truck transport of compacted corn stover</td>
<td>$7.05 ($6.40)</td>
<td>8.7</td>
<td>62.4</td>
</tr>
<tr>
<td>Combustion of corn stover[^c]</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$81.29 ($73.75)</strong></td>
<td><strong>100.0</strong></td>
<td><strong>936.2</strong></td>
</tr>
</tbody>
</table>

[^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 CH4/MJ and 0.0102 g of N2O/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/m³ (15 lb/ft³). 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 CO2e/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 CO2e/MJ of dry matter, which amounts to an 8 or 14 times reduction in GHG emissions compared to natural gas or coal fuels, respectively.

#### ACKNOWLEDGEMENTS

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#### REFERENCES


