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## **A Biomass Supply Logistics System**

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**Abstract.** *We evaluated a corn stover logistics system that included collection and transport by round bales to local storages within 3.2 km (2 miles) of the field during the fall harvest period. 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<sup>3</sup> (15 lb/ft<sup>3</sup>) 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, fossil energy consumption, and greenhouse gas (GHG) emissions for delivering the bulk corn stover to end users were \$85/t (\$77/ton), 936 MJ/t, and 114 kg CO<sub>2</sub>e/t, respectively, including nutrient replacement. The total fossil energy consumption was equivalent to approximately 7% of the energy content of the biomass. The life-cycle GHG emissions for heat and power applications were approximately 8 g CO<sub>2</sub>e/MJ of dry corn stover 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, Logistics, Tub Grinding, Roll Press Compaction, Net GHG Emissions.

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## Introduction

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). The user of biomass operates on an industrial cycle (year around time frame). 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 (square 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 has 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 cost more expensive (Sokhansanj and Turhollow, 2004; Sokhansanj et al., 2009).

One concept is to take bales stored at individual farm sites, chop or coarsely grind the biomass, compact it to a bulk density of at least  $240 \text{ kg/m}^3$  ( $15 \text{ lb/ft}^3$ ), and load it on trucks for delivery as a bulk product. Kaliyan et al. (2009) developed a tub-grinding/roll-press compaction system to increase the baled biomass bulk density to  $240 \text{ kg/m}^3$  ( $15 \text{ lb/ft}^3$ ). Achieving a bulk density of at least  $240 \text{ kg/m}^3$  ( $15 \text{ lb/ft}^3$ ) allows for transport of biomass in trucks that will load out based on maximum weight rather than volume. 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 goal of this paper is to evaluate a corn stover logistics system including: 1) collection and delivery to local storages within 1.6 to 3.2 km (1 to 2 miles) of the field in the fall, and 2) bale to bulk processing at the local storages followed by truck transport to the end user throughout the year. Performance measures include cost, life-cycle fossil energy input, and life-cycle greenhouse gas (GHG) emissions per tonne of biomass delivered to the end user. 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.

## The Proposed System

The different components of the proposed logistics system are discussed below. The life-cycle greenhouse gas (GHG) emissions related to the various logistics operations are estimated using the GHG emission metric “kg of  $\text{CO}_2$  equivalent per tonne of corn stover ( $\text{kg CO}_2\text{e/t}$ )”. The GHG emission metric of kg of  $\text{CO}_2$  equivalent per tonne of corn stover is calculated by using the 100-

year global warming potential (GWP) factors of 1 kg CO<sub>2</sub>/kg CO<sub>2</sub>, 25 kg CO<sub>2</sub>/kg CH<sub>4</sub>, and 298 kg CO<sub>2</sub>/kg N<sub>2</sub>O (IPCC, 2007): kg CO<sub>2</sub>e/t = [kg CO<sub>2</sub> + (25 × kg CH<sub>4</sub>) + (298 × kg N<sub>2</sub>O)]/t. In this study, we ignored the energy and GHG emission impacts related to the materials production, vehicle manufacturing, and disposal of farm machinery and other equipment.

### ***Collection and Transport to Local Storage***

The corn stover collection process includes shredding, raking, and round baling [567 kg (1250 lb) bales] followed by bale moving to a local storage within 1.6 to 3.2 km (1 to 2 miles) of the field after corn harvest in the fall. This process occurs in a 4 to 6 week period from October to mid-November.

Assumptions made for corn stover collection as round-bales and for the storage of bales at a local storage site are given in Table 1. Finding suitable time periods for shredding, raking, and round baling dry corn stover is a critical step in the collection process. We have also identified the step of bale moving from the field to the remote storage site as a critical step in terms of time management and costs. The distance from stover fields to remote storage sites is also a key factor in the logistics of this proposed system.

The capacities, cost, fuel/energy use, and GHG emissions related to various field operations are summarized in Table 2.

### ***Nutrient Replacement and Soil Organic Carbon***

We considered nutrient replacement for the material removed. 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 GHG emissions for the nutrient replacement.

We have not included changes in soil organic carbon (SOC) resulting from stover removal. Soil organic carbon 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); thus, we have not quantified them for this study.

Wilhelm et al. (2007) estimate allowable levels of corn stover removable to sustain soil organic carbon. 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 soil organic carbon for cases with lower yields, moldboard plowing, or corn-soybean rotations.

### ***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) (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 seven to eight 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 seven 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 ranges from 1 month 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.

### ***Bale to Bulk Processing at the Local Storage***

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<sup>3</sup> (15 lb/ft<sup>3</sup>), and loading trucks [22.7 t (25 ton) each] is modeled. 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).

Processing will occur throughout the year with mobile units moving from site to site. 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 operation at the site. Important operating information and cost data for bale to bulk processing are summarized in Table 5.

### ***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 corn stover was 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 miles) [i.e., 2/3 of radius]. 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 trucker returns to the remote site, he simply unhitches his empty trailer and hitches onto a trailer that is nearly full of compacted biomass. The average round-trip hauling distance assuming a winding factor of 1.3 is 84 km (52 miles). Doubling the radius would double the average round-trip hauling distance, but would increase the potential available amount of corn stover by a factor of 4. Cost, energy, and GHG emissions information 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<sub>2</sub> emissions are considered carbon neutral, methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions associated with the combustion must be considered. This amounts to 3.13 g CO<sub>2</sub>e/MJ of dry corn stover (GREET, 2009).

## **Results and Discussion**

Cost, life-cycle fossil energy consumption, and life-cycle greenhouse gas emissions for the corn stover logistics system are summarized in Table 7. The total cost, life-cycle fossil energy consumption, and life-cycle GHG emission for delivering roll-press compacted corn stover are \$84.87/t (\$76.99/ton), 936 MJ/t, and 114 kg CO<sub>2</sub>e/t, respectively.

The lower heating value (LHV) of dry corn stover is 16.7 MJ/kg (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 7.98 g CO<sub>2</sub>e/MJ of dry corn stover including corn stover combustion. The GHG emission value does not include any contribution for reduction in soil organic carbon. While there is uncertainty related to allowable removal levels, this is a reasonable assumption if a conservative approach to stover removal is followed.

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 65% 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 (36% out of 65%) 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 the logistics process.

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.

Truck transport to the end user contributes 8.3, 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 km (30 mile) to 96 km (60 mile) would increase total cost, life-cycle fossil energy use, and life-cycle GHG emissions by another 8.3, 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 km (30 mile) to 192 km (120 mile) would increase the area from which to draw corn stover by a factor of 16 with increased total cost, life-cycle fossil energy use, and life-cycle GHG emissions by 24.9, 20.1, and 12.7%, respectively. This suggests that the effect of increased transport distance on total cost and life-cycle GHG emissions with this type of logistics system may not be as great as for logistics system involving transport of lower density biomass.

## **Summary and Conclusions**

In this study, we modeled a corn stover logistics system that included collection and transport of corn stover as net-wrapped round bales to local storages within 3.2 km (2 miles) 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<sup>3</sup> (15 lb/ft<sup>3</sup>). The 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 \$85/t (\$77/ton).
- Fossil energy input is about 7% of energy in corn stover.
- Life-cycle GHG emissions are about 114 kg of CO<sub>2</sub>e/tonne including combustion, but excluding soil organic carbon loss.
- For heat and power applications, life-cycle GHG emissions for dry corn stover fuel are approximately 8 g CO<sub>2</sub>e/MJ, which amounts to an 8 or 14 times reduction in GHG emissions compared to natural gas or coal fuels, respectively.
- Collection/transport to local storage, local storage and loss, tub-grinding/roll-press compaction, and truck transport comprise almost 65% 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 8.3% to total cost, but only 4.2% to life-cycle GHG emissions.

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### **References**

- Anderson-Teixeira, K.J., S.C. Davis, M.D. Masters, and E.H. Delucia. 2009. Changes in soil organic carbon under biofuel crops. *GCB Bioenergy* 1(1): 75-96.
- Arthur, J.F., R.A. Kepner, J.B. Dobie, G.E. Miller, and P.S. Parsons. 1982. Tub grinder performance with crop and forest residues. *Trans. ASAE* 25(6): 1488-1494.
- ASBAE Standards. 2009. ASAE D497.5 FEB2006 Agricultural Machinery Management Data. St. Joseph, Mich.: ASABE.
- Brechbill, S., and W. E. Tyner. 2008. The economics of renewable energy: corn stover and switchgrass. Purdue Extension ID-404-W. West Lafayette, IN: Purdue University.
- Cundiff, J.S., and R.D. Grisso. 2008. Containerized handling to minimize hauling cost of herbaceous biomass. *Biomass and Bioenergy* 32(4): 308-313.
- Dec, R.T. 2002. Optimization and control of roller press operating parameters. *Powder Handling & Processing* 14(3): 222-225.
- Edwards, W., and D. Smith. 2008. 2008 Iowa farm custom rate survey A3-10. Ames, IA: Cooperative Extension Service, Iowa State University.
- GREET. 2009. The greenhouse gases, regulated emissions, and energy use in transportation (GREET) model. Version GREET 1.8c.0. Argonne, IL: Center for Transportation Research, Energy Systems Division, Argonne National Laboratory. Available at: [http://www.transportation.anl.gov/modeling\\_simulation/GREET/index.html](http://www.transportation.anl.gov/modeling_simulation/GREET/index.html). Accessed 7 July 2009.

- Hess, J.R., C.T. Wright, and K.L. Kenney. 2007. Cellulosic biomass feedstocks and logistics for ethanol production. *Biofuels Bioproducts & Biorefining* 1(3): 181-190.
- IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press. Available at: <http://www.ipcc.ch/ipccreports/ar4-wg1.htm>.
- Jenkins, B.M., J.F. Arthur, G.E. Miller, and P.S. Parsons. 1984. Logistics and economics of biomass utilization. *Trans. ASAE* 27(6): 1898-1904, 1910.
- Kaliyan, N., R.V. Morey, M.D. White, and D.G. Tiffany. 2009. A tub-grinding/roll-press compaction system to increase biomass bulk density: preliminary study. ASABE Paper No. 096658. St. Joseph, Mich.: ASABE.
- Lal, R., M. Griffin, J. Apt, L. Lave, and M.G. Morgan. 2004. Managing soil carbon. *Science* 304(5669): 393.
- Lazarus, W.F. 2008. Machinery cost estimates. St. Paul, MN: University of Minnesota Extension Service. Available at: <http://www.apec.umn.edu/faculty/wlazarus/documents/mf2008.pdf>.
- Morey, R.V., D.L. Hatfield, R. Sears, D. Haak, D.G. Tiffany, and N. Kaliyan. 2009. Fuel properties of biomass feed streams at ethanol plants. *Applied Engineering in Agriculture* 25(1): 57-64.
- Mukunda, A., K.E. Ileleji, and H. Wan. 2006. Simulation of corn stover logistics from on-farm storage to an ethanol plant. ASABE Paper No. 066177. St. Joseph, Mich.: ASABE.
- Nickel, R. 2008. Stop wasting hay. *Successful Farming* November 2008 issue.
- Petrolia, D.R. 2008. The economics of harvesting and transporting corn stover for conversion to fuel ethanol: a case study for Minnesota. *Biomass and Bioenergy* 32(7): 603-612.
- Pietsch, W. 1991. Size Enlargement by Agglomeration. New York, NY: John Wiley & Sons.
- Pilz, H., J. Schweighofer, and E. Kletzer. 2005. The Contribution of Plastic Products to Resource Efficiency. Vienna: GUA - Gesellschaft für umfassende Analysen. Available at: [http://www.resbrasil.com.br/upload/Plastics\\_GUA\\_LCA\\_completo\\_2\\_0105.pdf](http://www.resbrasil.com.br/upload/Plastics_GUA_LCA_completo_2_0105.pdf).
- Richey, C.B., J.B. Liljedhal, and V.L. Lechtenberg. 1982. Corn stover harvest for energy production. *Trans. ASAE* 25(4): 834-839, 844.
- Sawyer, J., and A. Mallarino. 2007a. Carbon and nitrogen cycling with corn biomass harvest. Integrated Crop Management IC-498(22), August 6, 2007. Ames, IA: Iowa State University Extension. Available at: <http://www.ipm.iastate.edu/ipm/icm/2007/8-6/cn.html>.
- Sawyer, J., and A. Mallarino. 2007b. Nutrient removal when harvesting corn stover. Integrated Crop Management IC-498(22), August 6, 2007. Ames, IA: Iowa State University Extension. Available at: <http://www.ipm.iastate.edu/ipm/icm/2007/8-6/nutrients.html>.
- Sheehan, J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, and R. Nelson. 2004. Energy and environmental aspects of using corn stover for fuel ethanol. *Journal of Industrial Ecology* 7(3-4): 117-146.
- Shinners, K.J., B.N. Binversie, R.E. Muck, and P.J. Weimer. 2007. Comparison of wet and dry corn stover harvest and storage. *Biomass and Bioenergy* 31(4): 211-221.
- Sokhansanj, S., and A. Turhollow. 2004. Biomass densification – cubing operations and costs for corn stover. *Applied Eng. in Agric.* 20(4): 495-499.
- Sokhansanj, S., and J. Fenton. 2006. Cost benefit of biomass supply and pre-processing. A BIOCAP Research Integration Program, Synthesis Paper, BIOCAP, Canada. Available at: [http://www.biocap.ca/rif/report/Sokhansanj\\_S.pdf](http://www.biocap.ca/rif/report/Sokhansanj_S.pdf). Accessed 8 May, 2008.

- Sokhansanj, S., A. Turhollow, S. Tagore, and S. Mani. 2006a. Integrating biomass feedstock with an existing grain handling system for biofuels. ASABE Paper No. 066189. St. Joseph, Mich.: ASABE.
- Sokhansanj, S., A. Kumar, and A.F. Turhollow. 2006b. Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). *Biomass and Bioenergy* 30(10): 838-847.
- Sokhansanj, S., S. Mani, A. Turhollow, A. Kumar, D. Bransby, L. Lynd, and M. Laser. 2009. Large-scale production, harvest and logistics of switchgrass (*Panicum virgatum* L.) – current technology and envisioning a mature technology. *Biofuels Bioproducts & Biorefining* 3(2): 124-141.
- Spatari, S., Y. Zhang, and H.L. MacLean. 2005. Life cycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles. *Environ. Sci. Technol.* 39(24): 9750-9758.
- Walters, D. 2008. Personal communication. Lincoln, NE: University of Nebraska, Department of Agronomy and Horticulture.
- Wilhelm, W.W., J.M.F. Johnson, D.L. Karlen, and D.T. Lightle. 2007. Corn stover to sustain soil organic carbon further constrains biomass supply. *Agron. J.* 99(6):1665-1667.
- Woodford, E. 2008. Personal communication. Redwood Falls, MN: Woodford Custom, Inc.
- Wright, C.T., P.A. Pryogle, N.A. Stevens, J.R. Hess, and C.W. Radtke. 2006. Value of distributed preprocessing of biomass feedstocks to a bioenergy industry. ASABE Paper No. 066151. St. Joseph, Mich.: ASABE.
- Zych, D. 2008. The viability of corn cobs as a bioenergy feedstock. Morris, MN: University of Minnesota, West Central Research and Outreach Center (WCROC). Available at: <http://renewables.morris.umn.edu/biomass/documents/Zych-TheViabilityOfCornCobsAsABioenergyFeedstock.pdf>.

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 (w.b.)	12.6 t/ha (200 bushels/acre)
Yield of stover as fraction of corn grain, dry matter/dry matter	1
Removal percentage of corn stover	70% when removed (removal every other corn year; average removal of 35% per year)
Corn stover moisture in round bales	15% (wet basis)
Corn stover removed per unit land area	7.4 dry t/ha (3.3 dry ton/acre) [8.7 wet t/ha (3.9 wet ton/acre)]
Weight of round bales [4 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 miles) [i.e., average round trip hauling distance in a 3.2 km (2 mile) radius with a winding factor of 1.3]

Table 2. Collection and local storage of corn stover by a farmer/custom operator.<sup>▲</sup>

Operation	Tractor/ power unit size, kW (hp)	Machine capacity	Fuel diesel use, L/t (gal/ton) *	Lubricant oil use, L/t (gal/ton) &	Cost, \$/t (\$/ton) <sup>‡</sup>	Life-cycle energy, MJ/t <sup>#</sup>	Life-cycle GHG emission, kg CO <sub>2</sub> e/t <sup>∇</sup>
Stalk shredding [ 6 m (20 ft) long]	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 [JD 705 Twin Rake, 9 m (30 ft) long]	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	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	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 <sup>Δ</sup>	13.13 <sup>Δ</sup>

<sup>▲</sup> Mass or weight is defined at 15% (wet basis) moisture content unless otherwise indicated.

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

& Oil consumption was estimated according to ASABE Standards (2009).

<sup>‡</sup> Average custom rate cost data given by Edwards and Smith (2008) and Woodford (2008).

<sup>#</sup> 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.

<sup>∇</sup> Life-cycle GHG emission (kg CO<sub>2</sub>e/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<sub>2</sub>e/MJ of fossil fuel] / 0.9072. GREET (2009) suggests an upstream emission factor and combustion emission factor of 17.23 and 73.64 g CO<sub>2</sub>e/MJ of diesel fuel, respectively, for farm tractors.

\*\* The baling cost includes the cost of net-wrap at 4 wraps per bale which is \$2.59/bale or \$4.56/t (\$4.14/ton).

<sup>Δ</sup> The total includes 55.59 MJ/t and 2.37 kg CO<sub>2</sub>e/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 and values chosen for this study.

Source	Nitrogen	Phosphorus (P <sub>2</sub> O <sub>5</sub> )	Potassium (K <sub>2</sub> O)
	kg/dry t (lb/dry ton)	kg/dry t (lb/dry ton)	kg/dry t (lb/dry ton)
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) and Zych (2008)	7.4 (14.8)	2.9 (5.9)	12.7 (25.4)
Petrolia (2008)	0.0 (0.0)	3.1 (6.2)	16.5 (33.0)
Brechbill and Tyner (2008)	7.9 (15.9)	2.9 (5.9)	15.0 (30.0)
Walters (2008)	8.2 (16.4)	NA *	NA
<b>This study</b>	<b>7.4 (14.8)</b>	<b>2.9 (5.9)</b>	<b>12.7 (25.4)</b>

\* NA = data not available.

Table 4. Nutrient replacement for corn stover removal.<sup>▲</sup>

Nutrient/ emission source	Fertilizer used	Price per unit mass of fertilizer, \$/t (\$/ton) <sup>#</sup>	Price per unit mass of nutrient, \$/kg (\$/lb)	Mass of nutrient replaced per unit mass of corn stover removed, kg/dry t (lb/dry ton)	Cost, \$/t (\$/ton)	Life- cycle energy, MJ/t *	Life-cycle GHG emission, kg CO <sub>2</sub> e/t *
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 <sub>2</sub> O <sub>5</sub> )	Diammonium phosphate	\$386.91 (\$351.00)	\$0.82 (\$0.37)	2.9 (5.9)	\$2.04 (\$1.85)	35.03	2.58
Potassium (K <sub>2</sub> O)	Potash	\$752.88 (\$683.00)	\$1.26 (\$0.57)	12.7 (25.4)	\$13.55 (\$12.29)	94.59	7.33
N <sub>2</sub> O emission from nitrogen fertilizer <sup>&amp;</sup>	--	--	--	--	--	--	39.03
N <sub>2</sub> O credit due to corn stover removal <sup>▼</sup>	--	--	--	--	--	--	-34.33
Total	--	--	--	--	\$19.26 (\$17.47)	412.74	31.04

<sup>▲</sup>Mass or weight is defined at 15% (wet basis) moisture content unless otherwise indicated.

<sup>#</sup> Quoted Fall 2009 Southwest MN prices.

\* The life-cycle energy for nitrogen, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O is 45.01, 13.97, and 8.76 MJ/kg of nutrient, respectively (GREET, 2009). The life-cycle GHG emission for nitrogen, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O is 2.61, 1.03, and 0.68 kg of CO<sub>2</sub>e/kg of nutrient, respectively (GREET, 2009).

<sup>&</sup> Nitrogen in N<sub>2</sub>O emitted as % of nitrogen in nitrogen-fertilizer = 1.325% (GREET, 2009).

<sup>▼</sup> Nitrogen in N<sub>2</sub>O avoided per unit of nitrogen in corn stover removed = -1.25% (GREET, 2009). The nitrogen content of corn stover = 0.69% (Morey et al., 2009).

Table 5. Bale to bulk processing of corn stover by an aggregator.<sup>▲</sup>

Operation	Tractor/power unit size, kW (hp)	Machine capacity, t/h (ton/h)	Fuel diesel use, L/t (gal/ton) <sup>*</sup>	Lubricant oil use, L/t (gal/ton) <sup>&amp;</sup>	Cost, \$/t (\$/ton)	Life-cycle energy, MJ/t <sup>#</sup>	Life-cycle GHG emission, kg CO <sub>2</sub> e/t <sup>▼</sup>
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 <sup>▲</sup>	403 (540) <sup>Ψ</sup>	22.7 (25)	4.507 (1.080) <sup>Ψ</sup>	0.020 (0.0048)	\$5.18 (\$4.70)	193.98	14.83
Roll-press compacting of tub-ground corn stover particles <sup>⊗</sup>	45 (60)	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

<sup>▲</sup>Mass or weight is defined at 15% (wet basis) moisture content unless otherwise indicated.

<sup>\*</sup> Diesel consumption was assumed to be 0.223 L of diesel per PTO kW per hour (0.044 gallons of diesel per PTO horsepower-hour) on average for each implement type (Lazarus, 2008).

<sup>&</sup> Oil consumption was estimated according to ASABE Standards (2009).

<sup>#</sup> 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.

<sup>▼</sup> Life-cycle GHG emission (kg CO<sub>2</sub>e/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<sub>2</sub>e/MJ of fossil fuel] / 0.9072. GREET (2009) suggests an upstream emission factor and combustion emission factor of 17.23 and 74.02 g CO<sub>2</sub>e/MJ of diesel fuel, respectively, for stationary reciprocating engines.

<sup>▲</sup> 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%; annual repair costs = 3% of first cost. The cost for insurance and housing is calculated based on procedures from Lazarus (2008).

<sup>Ψ</sup> Data for Vermeer TG5000 tub-grinder (Vermeer Corporation, Pella, IA; www.vermeer.com).

<sup>⊗</sup> 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%; annual repair costs = 3% of first cost. The cost for insurance and housing is calculated based on procedures from Lazarus (2008).

Table 6. Truck transport of compacted corn stover to users.<sup>▲</sup>

Operation	Power unit	Truck load, t (ton)	Fuel diesel use, L/t (gal/ton)	Lubricant oil use, L/t (gal/ton)	Cost, \$/t (\$/ton) <sup>*</sup>	Life-cycle energy, MJ/t <sup>#</sup>	Life-cycle GHG emission, kg CO <sub>2</sub> e/t <sup>∇</sup>
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

<sup>▲</sup>Mass or weight is defined at 15% (wet basis) moisture content unless otherwise indicated.

<sup>\*</sup> The cost of the dedicated Semi-truck transport is \$800 per day. In a day, Semi-truck can make 5 round-trips for a user located at 84 km (52 miles) per round-trip, totaling 418 km (260 miles) of driving per day.

<sup>#</sup> 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.

<sup>∇</sup> Life-cycle GHG emission (kg CO<sub>2</sub>e/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<sub>2</sub>e/MJ of fossil fuel] / 0.9072. GREET (2009) suggests an upstream emission factor and combustion emission factor of 17.23 and 74.35 g CO<sub>2</sub>e/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.<sup>▲</sup>

Operation	Cost		Life-cycle energy		Life-cycle GHG emission	
	\$/t (\$/ton)	%	MJ/t	%	kg CO <sub>2</sub> e/t	%
Payment to Farmer for Participation	\$7.50 (\$6.80)	8.8	--	--	--	--
Nutrient Replacement (N-P-K)	\$22.66 (\$20.56)	26.7	412.7	44.1	31.0	27.3
Collection/Transport to Local Storage	\$30.75 (\$27.90)	36.2	196.9	21.0	13.1	11.6
Local Storage Cost/Local Storage Loss <sup>#</sup>	\$3.41 (\$3.09)	4.0	30.5	3.3	2.2	1.9
Tub-Grinding/Roll-Press Compaction	\$13.49 (\$12.24)	15.9	233.7	25.0	17.9	15.7
Truck Transport of Compacted Corn Stover	\$7.05 (\$6.40)	8.3	62.4	6.7	4.8	4.2
Combustion of Corn Stover <sup>*</sup>	--	--	--	--	44.5	39.2
Total	\$84.87 (\$76.99)	100.0	936.2	100.0	113.5	100.0

<sup>▲</sup>Mass or weight is defined at 15% (wet basis) moisture content unless otherwise indicated.

<sup>#</sup> 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.

<sup>\*</sup> Combustion of corn stover in industrial boilers emits 0.0036 g of CH<sub>4</sub>/MJ and 0.0102 g of N<sub>2</sub>O/MJ of dry corn stover (GREET, 2009).

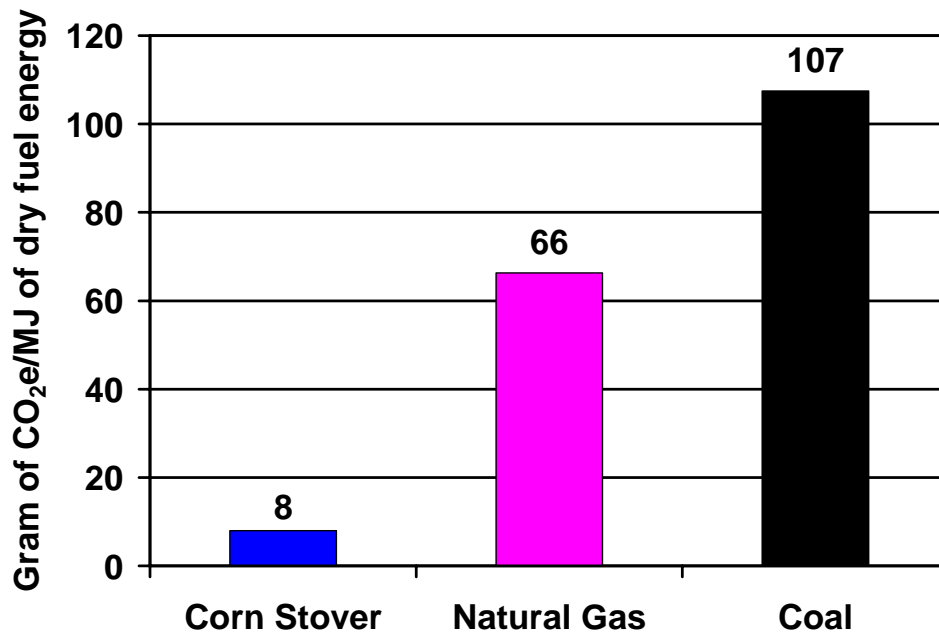


Figure 1. Life-cycle greenhouse gas emissions for heat and power applications. The GHG data for natural gas and coal include upstream (i.e., fuel production and transport) and combustion emissions as fuels in industrial boilers (GREET, 2009).