Field test and cost analysis of four harvesting options for herbaceous biomass handling

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Abstract: The nature of most biomass materials is a low bulk density as compared to traditional fuel sources. High handling cost could be a limiting factor in utilizing biomass feedstock. Understanding available harvesting machinery systems and associated costs is critical to future implementation. Four popular harvesting machinery systems were studied and costs were analyzed based on field measurements and calculations. These four systems included (1) round baling and round bale handling systems, (2) large square baling and square bale handling systems, (3) forage harvester and trucking systems, and (4) large square baling plus square bale compression systems. Results indicated that a self-loading forage wagon can reduce the cost to harvest a crop but requires more harvest time. Large square bales were found to reduce cost of handling and transport as compared to round bales. Further research is needed to determine storage costs and deterioration loss of the two bale types. Compressed square bales were found to reduce storage, handling and transport costs. Compressed bale machinery has a high initial cost, which currently makes only valuable for hay export.

Keywords: harvesting machinery system, herbaceous biomass, field, cost

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1 Introduction

Biomass materials are currently considered as possible feedstocks for biofuels. The main problems facing implementation is high handling cost and lack of logistics systems capable of handling sufficiently high tonnage of biomass materials year around[1]. Existing forage harvesting systems can be categorized into loose material harvesting and handling. These machinery systems are currently being utilized to harvest herbaceous biomass. Ensilage machine system is one example of loose material harvest method that uses a forage harvester and several forage trucks to harvest forage in a chopped format and store the chopped materials in silos. Another method of harvesting loose material is with a self-loading forage wagon, which can chop and collect forage from a windrow. The self-loading wagon uses considerably less energy and labor than the traditional forage harvesting system[2], though the field material efficiency of the self-loading wagon is much lower. The materials harvested with the self-loading wagon and forage harvesting systems are not contained by any twine or wrap. These materials are referred to as loose biomass hereafter.

Forage harvesters are designed to harvest materials with high moisture contents and may experience friction and combustion problems with dry materials. A forage harvester was evaluated in Europe for harvesting miscanthus (*Miscanthus x giganteus*) at 11 mm and 44 mm chop length, which resulted in a bulk density of 95 and 70 kg/m^3 (dry matter), respectively[3]. Despite the benefits of using a self-loading wagon, the self-propelled forage harvester is commonly used for

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harvest wet biomass considering field efficiency. Herbaceous biomass does not need to meet animal nutrition requirements. This allows the biomass to be left in the field longer as it does not need to meet quality requirements. This flexibility allows farmers a longer time window to harvest biomass. Self-loading wagons do not need transport trucks, and rely on tractor power to harvest and transport. Therefore, the self-loading wagon might be a viable method to reduce biomass harvest fuel consumption and labors needed.

Previous field studies have evaluated a self-loading wagon and a forage harvester systems in different fields and crops[4]. The wagon system has a specific range of distance and moisture content when harvesting at maximum efficiency. The wagon system used less fuel and man-hours compared to the forage harvester system for every test conducted. The forage harvester system always harvested almost twice as fast in hectares per hour, with a significantly smaller chop length. Comparing the man hours used per hectare harvested, the forage harvester system was 45% to 69% as efficient compared to the wagon system. For farms looking to implement a self-loading wagon system, consideration must be given to the time required to harvest each year, and the average distance from the field to unloading site. Secondary consideration should be the maximum acceptable chopping length required for animal feeding. Overall the wagon system can save a considerable amount in fuel and labor costs, when running at optimal conditions including sufficient material in windrows, large field to fully load the wagon, and within 2 km average transport distance.

The use of balers to harvest herbaceous biomass is well documented. Round balers densify the biomass by packing and rolling. Large square balers densify “flakes” of biomass, and then compress the flakes into bales. Prewitt et al.[5] baled corn stover and achieved densities up to 176 kg/m^3. Cundiff and Marsh[6] found the density of switchgrass bales to be 143 kg/m^3 and 200 kg/m^3 for round and large square bales, respectively. Field storage is also preferable with round bales, and round balers require less energy to run. Sokhansanj and Turhollow[7] also found that round balers reduce cost compared to square balers when harvesting corn stover. Baler manufacturers are trying to develop high density bales to reduce transportation costs. The Krone Big Pack 1290HDP large square baler is an example of a machine that can increase the weight of a bale by up to 20% compared to standard baler models. Handling and transporting square bales may be an option to handle biomass if an efficient and effective technique can be found. Square bales, however, have the disadvantage of large mass loss due to deterioration if stored in a field without adequate covering. Baling also relies on the local weather conditions, field conditions while harvesting, and the requirements for bioenergy production. If the biomass cannot be dried due to weather restrictions, the harvest and handling systems must be able to process the wet material for biomass quality reasons. Baling may not be the most suitable technology in this case.

Densification and preprocessing refer to the handling steps that occur on the farm level in order to minimize storage and transport costs. Preprocessing usually indicates size reduction and moisture content adjustment while densification indicates an increase in bulk density. Lam et al.[8] have shown that bulk density increases as particle size decreases. Integrating size reduction into the field harvesting operations might reduce the overall cost of biomass feedstock supply[9]. Wright et al.[10] reported that distributed preprocessing at the field-site or a fixed preprocessing facility could reduce cost and provide a higher value feedstock. Most literature focuses on using hammermills due to the lower maintenance associated with operating costs[11]. Van Pelt[12] tested densification of corn stover and other biomass, and found relationships and formulas that relate the energy applied to the density achieved. With these relationships power required to densify a specific biomass can be determined. Densification is currently used on almost all farm level hay harvesting procedures. Densification needs to be utilized in any herbaceous biomass handling system to minimize handling and storage costs.

To avoid the dangers of combustion fire associated with wet bales, the harvest and transport of loose material has been of extreme interest. Turhollow and Sokhansanj[13] studied the transport of wet corn stover at 75% moisture and found limited circumstances where transport would be feasible. Research has also focused on comparing baled material with chopped loose silage material, with the findings showing silage not competitive with dry hay bales based on transport and harvest costs[14]. Loose biomass could theoretically load a truck to 65% of axle weight with a density of around 130 kg/m^3[15]. This means that any extra loading of material over 65% of axle weight into the truck would result in increased transport efficiency. There is no current machine system transport based completely on transporting loose material.

Large square hay bales are currently compressed to transport overseas. This densification is expensive due to high machinery investment cost; but it can be justified due to the high demand for hay in Eastern countries. Current bulk density of large square hay bales is between 120 and 180 kg/m^3, but a bale compressor from Steffen Hay Inc. could compress the bale and double the density[16]. However, bale compression is currently only applied to long distance forage sales because the cost of bale compression is \$33 per mg (wet)[17] ("mg" means milligram). The economic performance of the bale compression system needs to be studied when the bale compression is integrated into biomass handling. Some large square bales of hay have already been transported with highway trucks; but fully-use of the load capacity of highway trucks within the dimension limit is a challenge. Time used for loading and unloading are also of concern. A study of biomass bale compression is needed to compare to loose and round bale handling systems.

The objectives of this study were (1) To measure field performance of harvesting energy crops by using different harvest systems; (2) To analyze costs of these systems and compare potential uses in biomass harvest.

2 Herbaceous biomass harvest field tests

2.1 Crops and equipment used

Field tests were conducted in 2009 in four switchgrass fields located at Ernst Conservation Seeds, Meadville, Pennsylvania, United States. The switchgrass variety was "Blackwell", which is a high producing variety that performs well on poor soil.

Three harvesters used in the field studies: one round baler, one large square baler, and a self-loading forage wagon. The round baler used was a New Holland BR7070 with Crop-Cutter (Figure 1). The Crop-Cutter is a knife grid that is used to chop the crop upon feeding into the baler. This function allows farmers to create a bale that is easier to feed to livestock. The crop-cutter mechanism was disengaged by lowering the knife grid out of the material path in this test. The large square baler used was a Case-IH LB433 (Figure 2). This large square baler has a mechanism for cutting the crop similar to the round baler discussed above. The mechanism was also disengaged for this study. The same tractor, a CaseIH 210 Puma with gross engine power of 157 kW, and PTO power of 134 kW, pulled both balers.

Figure 1 New Holland BR7070 round baler and CaseIH 210 Puma tractor

Figure 2 CaseIH LB433 square baler and CaseIH 210 Puma tractor

Two fields were used to test a self-loading forage wagon (Figure 3). Field 1 had a distance of 4 km to a storage location where the machine dumped the harvested materials. Materials harvested in field 2 were dumped in a plot right beside this field referred to as in-field unloading. Switchgrass bales were stored to be converted into briquettes on farm or saved for bale compression tests. All fields to be harvested were mowed in advance. The material was allowed to dry to adequate moisture content before raking or merging of the windrows. The switchgrass had less than 15% (d.b.) moisture by the time of harvesting.

Note: It is used in loose material collection and driven by the Puma 210 tractor

Figure 3 The self-loading wagon (Pöttinger Jumbo 8000)

Material for tests by using both balers was raked or merged so that each system harvested two windrows of similar mass and volume. Switchgrass windrows were collected using the self-loading wagon, which was also operated with the Puma tractor. The wagon has a cutting mechanism located behind the pick-up head. The function of this mechanism is to force the crop through a set of stationary knifes and into the wagon. The theoretical cutting length was 34 mm with the practical cutting length of 50 mm. This machine can pick-up and cut crop windrows, and is, hereafter referred to as the Wagon system.

2.2 Test procedures and measurements

The tractor was fueled in field-side and harvesting started when windrows were merged, and moisture content was appropriate to harvest. All field measurements started at the moment machines started moving to commence harvesting the windrowed material. Measurements in all field tests included all parameters relative to the field performance of a machine system. Time to complete each of field operations was recorded and used to determine the field efficiencies of machines. Time was recorded by multiple sources to ensure an accurate measurement using digital watches and video. These sources were analyzed later and used to verify in-field data. Researchers were positioned field-side and also in the cabs of the tractors. Research personnel were provided with digital watches that were synchronized prior to tests. The researchers completed a data record sheet while completing the tests ensuring that all times were recorded. Field tests were also recorded with digital camcorders allowing later examination and verification of field operating times recorded during the tests.

Fuel consumption of baling was measured by filling the fuel tank of the tractor before and after tests. The tractor was fueled after every two windrows by weighing a fuel can full, and filling the tractor, then weighing the can with the remaining fuel using a portable scale. This method was found to be extremely accurate.

The switchgrass bales were transported to the scale and weighed prior to storage. Each baler was given the same amount of material, the baler collected two windrows, and then was fueled, and it collected two more windrows. After the final fueling, the tractor switched balers and repeated the process. After the material was collected, both balers were moved to the next field to be harvested. Switchgrass harvested with the wagon was transported to the scale and weighed prior to being unloaded in a bunker for use as dairy cow bedding on Ernst farm. The wagon system was fueled after every load and fueled after returning from unloading. To evaluate the impact of transport on machine field efficiency, the wagon was tested in two fields. The distance from one field to the dumpsite was 4 km and harvested switchgrass was dumped in field for the other field.

After tests were completed all the bales were collected and weighed. Crop samples were taken from random locations in the field immediately before the baler harvested the sampled material. These samples were weighed, stored in air tight plastic bags, and later oven dried to determine moisture content.

2.3 Results and discussion

The amount of biomass collected was the result of biomass available for harvest in a one day period. A replication was defined as two windrows harvested to produce multiple bales. Round and square balers were operated in the same field in randomly selected windrows. Seven large square bales were made in each test (Table 1). From the large square bales created ten were selected to be transported to the bale compressor site. A replication for the wagon was defined as a full load. When the wagon was fully loaded, it transported to either an in-field site (for field 1) or a remote dumpsite (for field 2) to unload.

Table 1 Summary of field experiments on Ernst farm

Field	Harvest form	Time/h	Replication	Av. weight per replication/kg	Total weight/Mg	Av. time/h·Mg^{-1}	Fuel use/L·Mg^{-1}	Travel distance/km
1	Loose	1.105	4	4 639	18.55	0.0596	1.71	0
2	Loose	4.410	5	2 869	14.35	0.3074	5.70	4.0
3	Round	0.300	10	260	2.60	0.1152	1.85	
	Square	0.250	7	461	3.23	0.0774	1.76	
4	Round	0.450	11	299	3.29	0.1370	2.72	
	Square	0.317	7	453	3.17	0.0999	2.53	

Note: "Mg" means "million grams". One "Mg" is a metric ton.

The baled material on the Ernst farm was harvested in the spring after the switchgrass had ended growing and leached nutrients back into the soil over the winter. The new switchgrass shoots were growing and were approximately 0.305 m high when the old switchgrass was harvested. Ernst farm harvests switchgrass for seed, and then baled biomass, which was left in field after seed harvest. This seed harvest reduced biomass yield; the biomass yield was also reduced by lodging of material due to winter snow. This type of harvest is more sustainable due to the nutrient recycling; but, it resulted in greater a mass loss than baling in the fall.

Baled herbaceous biomass is utilized on farms, and is currently proposed for use in most biomass handling systems. Bales have many advantages due to the density and the portability. It has not yet been determined the optimum density of bale to facilitate transport. Large square bales also show promise for handling biomass due to their ease of portability as compared to round bales. Baled material should not be created over 15% moisture, due to increased mold activity resulting in increased heat and fire risk. This may poise a concern for large scale operations, as biomass may not be available under this moisture level in typically rainy areas. Bale fires would also be devastating to plant utilizing biomass for power, as the plant would be contracted for a specific amount of power per day. This illustrates the need to have biomass stored at various locations to decrease the risk associated with spontaneous combustion.

3 Bale compression tests

3.1 Facilities used for bale compression

Large square bales were compressed with a commercial machine as shown in Figure 4 (Steffen Systems, 2882 Howell Prairie Road, NE Salem, Oregon, USA). A diesel engine (Cummins C8.3P) of 186 kW supplies power to the compressor. This engine draws fuel from a 946 liter tank and returns the unused fuel back to the tank.

Ten large square bales collected from the Ernst field baling test were transported to the compressor located at Heidel Hollow Farm in Germansville, PA. This compressor is for bale recompressing and resizing and producing small compressed bales that are easy to handle by hand. This machine slices a large bale (0.9 m ×1.3 m ×2.4 m) into three pieces of (0.9 m ×0.4 m ×2.4 m), and then compress each slice one by one. Each compressed bale is forced through a set of three stationary knifes to make small compressed bales. These small bales, now weighing 34 kg (75 lb.) or less will then be re-twined. In this test, two of these stationary knifes were removed to reduce the energy consumption caused by bale slicing.

Figure 4 Commercial large square bale compressor (Heidel Hollow Farm, Germansville, PA)

3.2 Tests procedures and measurements

Primary measurements included fuel consumption of the bale compressor and time required for each of the operations involved. Secondary measurements were size and weight of bales before and after compression, and moisture contents of the bale materials.

The compression required three operators; one to load large bales and one to unload compressed small bales; one to operate compression. A bale handler picked up two large bales at a time, and then these two bales were placed on a table which fed the bales through a cutter. After cutting, the bale sections were compressed then cut in half. After the final cutting, the bales were lifted by hand onto a pallet. A pallet held a maximum of twenty small bales, and was moved with a fork lift. One worker operated both bale handler and forklift. One operated the compressor, and one loaded the compressed bales unto pallets. Ten bales were compressed without interruption, and placed the compressed bales in a storage area.

At the compressor, the time to compress, fuel consumption, and weight of the bales were measured. A digital video camera was used to record the complete compression tests for later examination. The time required for the test was recorded by reviewing the video after the test. The bales were weighed upon arrival to the compressor with an in-ground scale. The compressed small bales were also weighed after the tests. The dimensions of the input bales and the output bales were manually measured and recorded before and after compression. Fuel flow rates were measured in both in and return lines (Figure 5). Each fuel line was fitted with a flow meter, which were sized by consulting with the engine manufacturer. The fuel flow rate and time were recorded for each bale by taking readings from each on the flow meters.

Figure 5 Flow meters and fuel tank providing fuel to compressor engine

3.3 Results and discussion

Test results were processed to calculate the hours per mg and liters of fuel per mg required compressing bales (Table 2). A fuel reading was taken when each of the ten bales entered into the first section of the compressor. The fuel use for each bale was calculated by subtracting the fuel use reading at the next bale by the fuel use reading at the current bale. This calculation yields nine fuel use readings taken in between the ten bales. The compressor utilized an average of 0.95 L of fuel per bale, and took an average of three minutes and three seconds to compress each bale.

One large bale had a dimension of 0.86 m×1.22 m×2.21 m, and the resulting bales were 0.53 by 0.46 by 0.38 m, when stacked in groups of 20 on a pallet they had a dimension of 1.02 m×1.17 m×1.70 m. The initial bales had a combined volume of 23.27 m^3, when accounting for the 7.0% mass and water loss due to compression this volume is 21.67 m^3. The compressed small bales had a combined volume of 13.13 m^3, a reduction in volume to 60.6% of initial size. If the compressed small bales were stacked without a pallet they would have a volume of 11.98 m^3, a reduction in volume of 55.3% of initial size. The bales had an average of 14.1% moisture (w.b.) at the time of compression.

Table 2 Time and fuel uses of the large square bale compressor

Bale No.	Fuel used /L	Time /h	Time efficiency /h·Mg^{-1}	Fuel efficiency /L·Mg^{-1}
1	0.7192	0.0656	0.1558	1.7087
2	0.6435	0.0386	0.0917	1.5289
3	0.9085	0.0528	0.1253	2.1581
4	0.7949	0.0358	0.0851	1.8886
5	0.7192	0.0375	0.0891	1.7087
6	1.2870	0.0689	0.1637	3.0577
7	1.325	0.0553	0.1313	3.1475
8	0.8706	0.0336	0.07981	2.0684
9	1.1735	0.0689	0.1637	2.7878
Average	0.9195	0.05078	0.1104	2.1844
Std. Dev.	0.3277	0.01477	0.0421	0.7785

The nature of this bale compressor allows the processing of only large square bales that were not created using a Crop-Cutter or similar pre-processing. The Crop-Cutter is a knife grid that mechanically reduces biomass size. An alternate mechanism performing the same size reduction would be a combine, which expels chopped straw. The bales that have been pre-processed using a knife grid could possibly expand upon compression. The strings of the bale may not be able to tie due to the cuts in the bale.

Compressed large square bales are currently only used for long distance transport of high value hay products. These compressed hay bales are currently transported overseas, and the compression costs are offset by the high shipping costs. Compression costs can account for over $16 per wet ton of biomass compressed. The high cost of compression needs to be offset with savings in transport costs to make compression feasible. The feasibility will be further explored in the modeling section.

4 Cost analysis

The fixed cost of each machinery system is an aspect that will greatly affect the total cost per ton to harvest biomass. The fixed costs need to be annualized into a per ton basis to allow easy implementation into a model. This per ton cost can also be easily compared against custom rates. Custom rates are the rates that an operator will charge to harvest a given acreage, or amount of biomass. Custom rates for hay harvest give a good estimation for harvesting switchgrass, as the machinery used is the same.

4.1 Loose material machinery costs

The machinery selected to handle loose material was a self-loading forage wagon (Figure 3). The self-loading wagon was selected as the most economical choice for harvesting loose material. The downside of harvesting biomass with this wagon is a longer harvest time as compared with a forage harvester and truck system. This longer time will not be as great a factor in biomass handling as the material can be a lower quality, and can sit in the field for longer periods of time. One scenario of harvesting herbaceous biomass at 4 km, was examined (Table 1). At an average of 4-km travel distance, the wagon will travel between zero and 5.55 km to pick up the biomass (Figure 6). A 5.6-km radius circle will encompass 101.66 km^2 or 10 166 ha of land. Assuming that 50% of the land is used for biomass production, then 5 083 ha of land within 5.55 km radius will be covered with biomass. Assuming 6 Mg/ha as a good yield of biomass for Pennsylvania, there is 32 929 mg total to harvest.

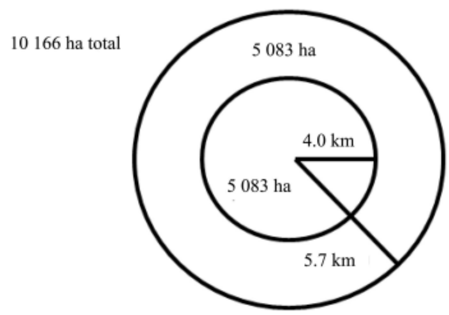

Figure 6 Acreage covered by self-loading wagon

A self-loading wagon is a substantial investment at $125 000. This breaks down to $14 750 per year using

Equation 1[18] where salvage value (S_v) is 20%, life (L) is 10 years, interest (I) is 3%, and other costs (K_2) are 2%. Including repair and maintenance of 50% this number is \$22 125 per year. A tractor sized to match the wagon will cost around \$30 per hour of use including ownership cost, housing, lubrication, repair, maintenance, and tax. By dividing \$22 125 by 32 929 Mg, this comes to \$0.67/Mg. The tractor cost of \$30 per hour divided by a speed of 16.8/Mg per hour adds \$1.79 mg to the total cost. The cost including fuel and labor of \$.79 and \$15 respectively is \$1.37/Mg \$0.89/Mg. This total cost is \$4.05/Mg to harvest biomass.

$$C_0 = 100\left[\frac{1-S_v}{L} + I\frac{1+S_v}{2} + K_2\right] \tag{1}$$

4.2 Round baling machinery costs

The round baler and tractor costs comprise a significant amount of the total harvest costs. The total cost per bale is \$1.04 for the baler and \$1.39 for the tractor. This gives a total machinery cost of \$2.43 per bale. With data from Tables 1 and 3 the average for round bale harvesting is 0.1258 h/Mg, and 2.284 L/Mg. Assuming the average weight of a round bale is 279 kg (Table 1) harvested at 0.0352 hours per bale and 2.29 liters per bale. Assuming labor costs are \$15/h and fuel is \$0.79 L, the labor and fuel costs are \$0.528 per bale for labor and \$0.505 per bale for fuel. This gives a total cost of \$3.46 per bale. The average rate for custom round bale harvesting in Pennsylvania is \$7.30 per bale weighing an average of 395 kg[19]. By dividing \$7.30 by 395 kg and multiplying by the weight of our bale 276 we arrive at \$5.16 per bale. This custom rate and the calculated rate differ by 33%, which can be attributed to profit and taxes.

4.3 Large square baling machinery costs

The round baler and tractor costs comprise a significant amount of the total harvest costs. The total cost per bale is \$2.99 for the baler and \$1.76 for the tractor. This gives a total machinery cost of \$4.75 . Using data from Tables 1 and 3 the average for large square bale harvesting is 0.08865 h/Mg, and 2.15 L/Mg. Assuming the average square bale is 457 kg (Table 1), the harvesting rate is 0.0405 hours per bale and 0.9797 liters per bale. Assuming labor costs are \$15/h and fuel is \$0.79/L, the labor and fuel costs are \$0.608 per bale for labor and \$0.776 per bale for fuel. This gives a total cost of \$5.80 per bale. The average rate for custom large square bale harvesting in Pennsylvania is \$8.20 per bale weighing an average of 380 kg[19]. By dividing \$8.20 by 380 kg and multiplying by the weight of our bale 456 kg we arrive at \$9.84 per bale. This custom rate and the calculated rate differ by 41%, which can be attributed to profit and taxes.

4.4 Bale compression machinery costs

A commercial bale compressor is not a separate handling system; rather it is an addition to the large square bale system. The bale compressor will aid in handling and transporting bales by shrinking the bale size thereby increasing the density. The total machinery cost for the compressor is \$12.23/Mg (Table 3). From Table 2 the compressor runs an average of three minutes and three seconds per bale and used 0.895 L of fuel per bale. The bales averaged 421 kg per bale. Converting to a per ton basis 0.1217 h/Mg and 2.267 L/Mg are required for compressing. Assuming labor costs are \$15/h and fuel is \$0.79/L, the labor and fuel costs are \$1.830 mg per person and \$2.30/Mg. Using two laborers the total price would be \$23.19/Mg to compress the large square bales.

4.5 Summary of cost analyses and field results

Table 3 summarizes the combined costs for each system. The loose material is transported by the harvester (self-loading wagon and tractor), at \$30 h and at 24 km/h this cost is \$1.25 per loaded km. The transport costs of bales are derived using a base line cost of \$1.25 per loaded km for commercial tractor-trailer transport. The loose material, round and square bales transportation can hold 4.6, 9.1, and 17.7 Mg of biomass, respectively. The compressed bale transport can theoretically hold 1.8 times the material that a square bale transport can this would be 28.6 Mg of material. This is the overall maximum limit of highway. Local road hauling limits will be the limiting factor. Using \$2 per mile (3.2 km) as a typical highway shipping cost, it can be found that \$0.39 per mile (\$0.26/km) for the loose material harvesting system. The baled material handling and satellite storage (SSL) costs are taken from research done by Sokhansanj et al.[20] . This research found that trucking costs for square bales were comprised of a base cost of \$5.70/Mg and a variable cost of 0.1367 \$ per mile per Mg. This formula was used to create Table 4, where the base costs are at the SSL and the variable costs are in the transportation column.

Table 3 Machinery costs

Description	Unit	Round baling		Large square baling		Square bale compression	
		Baler	Tractor	Baler	Tractor	Compressor	Fork Lift
Purchase price	\$	20 000	90 000	90 000	100 000	480 000	50 000
Design life	h	1 500	12 000	3 000	12 000	15 000	15 000
Hours per day	$h \cdot d^{-1}$	10	10	10	10	10	5
Days per week	$d \cdot (wk)^{-1}$	5	5	5	5	5	5
Weeks per Yr	$wk \cdot a^{-1}$	4	4	4	4	30	30
Annual use	h	200	200	200	200	1 500	750
Interest	%	0.08	0.08	0.08	0.08	0.08	0.08
Insurance	%	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025
Tax	%	0.01	0.01	0.01	0.01	0.01	0.01
Repair/maintain	$\$ \cdot h^{-1}$	0.9	1	0.75	1	10	7
Salvage value	%	0.1	0.1	0.1	0.1	0.1	0.1
Capacity	$Mg \cdot h^{-1}$	7.95	7.95	11.44	11.44	7.26	7.26
Machine life	a	7.5	60	15	60	10	20
Ownership cost	$\$ \cdot a^{-1}$	5 930	7 935	14 985	8 817	70 320	5 075
Ownership cost	$\$ \cdot h^{-1}$	29.65	39.68	74.93	44.08	46.88	6.77
Cost per mg	$\$ \cdot Mg^{-1}$	3.73	4.99	6.55	3.86	7.84	4.39
Total cost	$\$ \cdot Mg^{-1}$	8.72		10.41		12.23	

Table 4 Summary of handling and transport costs

Handling system	Field costs /$\$ \cdot Mg^{-1}$	SSL costs /$\$ \cdot Mg^{-1}$	Transport costs /$\$ \cdot (mg \cdot km)^{-1}$
Loose material	4.71	–	0.27
Round bales	12.40	13.83	0.33
Large square bales	12.71	6.91	0.17
Compressed bales	–	21.59	0.08

Bale densification technology was proposed for reducing handling costs of herbaceous biomass. A commercial bale compression machine was evaluated and the operational cost of compressing large square bales of switchgrass was \$18.13/Mg (wet mass). The bales were compressed to 55.3% of their normal volume, when placed on pallets the resulting 20 small bales would take up 60.6% of the original size. Compression of wet biomass was not evaluated.

Table 4 outlines the complete costs for handling and transporting loose biomass, round bales of biomass, large square bale, and compressed large square bales. From this table the compression costs are \$21.59/Mg and the baled cost is \$6.91/Mg. This difference is a cost of \$14.68/Mg; saving \$0.09/Mg per km with the systems tested. A distance of greater than 179 km would be required to offset the compression cost with transport savings. The compressor is currently used for high value hay exporting, which transports hay over long distances. The fact that the compressor is not currently used for local hay transport validates the long distance calculated. The transport process will also be drastically affected by the fuel input costs. As the fuel costs rise the compressor will save more money in transport costs. Compressed bales will also reduce storage costs as compared to a standard square bale. A compression of 50% of normal bale volume would result in a large savings for storing the bales. Storage savings are not specifically studied in this research. In addition, this compressor is not designed for biomass production.

The long transport distance allowing for the compressor to break even illustrates the need for a redesign of the compressor. The compressor costs primarily come from the high machinery costs and fuel consumption. These costs can be reduced by designing a less complex compressor. Further work should focus on compressing a whole large square bale without dividing it into multiple sections. Wet material should also be researched for compression; wet herbaceous biomass requires less energy to compress, compression may also limit oxygen resulting in an anaerobic storage environment. A redesign should also contain methods to increase throughput speed of the compressor and the reduction of labor to only one person.

5 Conclusions

Crop harvest and handling methods contribute significantly to the total cost of biomass implementation. Biomass crops can remain in the field longer as compared to traditional forages. This extra time in the harvest window can allow more cost efficient machinery to harvest the crop. A self-loading forage wagon can reduce harvest costs as compared to a forage harvester, especially if the travel distance allows the wagon to spend more time harvesting than traveling.

Large square bales have an advantage over round bales due to their ability to stack and transport with ease. In the scope of this research, large square bales were found to yield significant cost savings due to the ease in which they can be handled and transported. Round bales have an advantage during storage; they can shed water and may have lower mass loss due to deterioration. Future research should focus on a comparison between square and round bales stored in various locations.

Bale compression was found to be a valuable addition to the large square bale handling system. Compression reduces volume of the bale thereby reducing storage cost, handling cost, and transport costs. The high cost of compression limited the feasibility of implementation into a biomass system. Therefore a redesign of compression machinery is desirable, focusing on creating a dense bale and reducing fuel use.

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[References]

[1] BRD (Biomass Research and Development Board). 2008. National Biofuels Action Plan. NBAP081208. Washington, DC: U.S. Department of Energy.

[2] Tremblay D, Savoie P, Theriault R. Self-loading wagon power requirement for coarse chopping of forage. Canadian Agricultural Engineering, 1991; 33(1): 31–38.

[3] Venturi P, Huisman W, Molenaar J. Mechanization and costs of primary production chains for Miscanthus x giganteus in the Netherlands. Journal of Agricultural Engineering Research, 1998; 69(3): 209–215.

[4] Brownell D K, Liu J, Hilton J W, Richard T L, Cauffman G R, Macafee B R. Evaluation of two forage harvesting systems for herbaceous biomass harvesting. In: ASABE Annual International Meeting. Reno, Nevada, 2009.

[5] Prewitt R M, Montross M D, Shearer S A, Stombaugh T S, Higgins S F, McNeill S G, et al. Corn stover availability and collection efficiency using typical hay equipment. Transactions of the ASABE, 2007; 50(3): 705–711.

[6] Cundiff J S, Marsh L S. Harvest and storage costs for bales of switchgrass in the southeastern United States. Bioresource Technology, 1996; 56(1): 95–101.

[7] Sokhansanj S, Turhollow A R. Baseline cost for corn stover collection. Applied Engineering in Agriculture, 2002; 18(5): 525–530.

[8] Lam P S, Sokhansanj S, Bi X, Lim C J, Naimi L J, Hoque M, et al. Bulk density of wet and dry wheat straw and switchgrass particles. Applied Engineering in Agriculture, 2008; 24(3): 351–358.

[9] Wright C. Full-scale field grinding and transporting tests using multiple feedstock varieties. In: Agricultural Equipment Technology Conference (AETC), ASABE. Louisville, Kentucky, 2008..

[10] Wright C, Pryfogle P A, Stevens N A, Hess J R, Radtke C W. Value of distributed preprocessing of biomass feedstocks to a bioenergy industry. ASABE Paper No. 036082. St. Joseph, Mich: ASABE, 2006.

[11] Yu M, Womac A R, Pordesimo L O. Review of biomass size reduction technology. ASABE Paper No. 036077. St. Joseph, Mich: ASABE, 2003.

[12] Van Pelt T J. Maize, Soybean, and Alfalfa Biomass Densification. CIGR Journal of Scientific Research and Development Manuscript EE 03 002, 2003.

[13] Turhollow A F, Sokhansanj S. Costs of harvesting, storing in a large pile, and transporting corn stover in a wet form. Applied Engineering in Agriculture, 2007; 23(4): 439–448.

[14] Worley J W, Cundiff J S. Comparison of harvesting and transport issues when biomass crops are handled as hay vs silage. Bioresource Technology, 1996; 56(1): 69–75.

[15] Cundiff J S, Grisso R D, Shapouri H. Economic analysis of

two receiving facility designs for a bioenergy plant. ASABE Paper No. 076051. St. Joseph, Mich: ASABE, 2007.

[16] Steffen Systems. High density bale compression systems. 2009. http://www.steffensystems.com/Products/Bale_Press/index.htm. Accessed on [2009-10-07]

[17] Miles T. Communications with T.R. Miles, Technical Consultants, Inc. http://www.trmiles.com. 2008.

[18] ASAE Standards. EP496.2: Total annual ownership costs --Agricultural Equiptment. St. Joseph, Mich: ASAE. 2000.

[19] Pike A W. Machinery Custom Rates. Harrisburgh, Pa. 2009. http://www.nass.usda.gov/Statistics_by_State/Pennsylvania/Publications/Machinery_Custom_Rates/custom09.pdf. Accessed on [2009-10-07]

[20] Sokhansanj S, Mani S, Turhollow A, Kumar A, Bransby D, Lynd L, et al. Large-scale production, harvest and logistics of switchgrass (*Panicum virgatum* L.) - current technology and envisioning a mature technology. Biofuels, Bioproducts & Biorefining-Biofpr, 2009; 3(2): 124–141.