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WHOLE-PLANT CORN HARVESTING FOR BIOMASS: COMPARISON OF SINGLE-PASS AND MULTIPLE-PASS HARVEST SYSTEMS

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Abstract. *The economic potential of several different harvest and storage scenarios for single-, two-, and three-pass wet harvesting systems for corn stover were evaluated. An economic analysis of a representative farm was used to estimate costs of harvest, storage, and transport of corn stover to assess the most economically promising of the conceived machine configurations. A grain combine with crop unit modified to chop and blow the stalk and leaf fraction was estimated to produce stover at $30.8/dry Mg harvested, stored and delivered to the processing facility. This cost was $41.9/dry Mg for a conventional system with dry bales stored outdoors, so the single-pass system was estimated to reduce costs by 26%. Two- and three-pass wet stover systems using a self-propelled forage harvester reduced delivered cost by 19 and 15%, respectively.*

Keywords. Biomass, corn stover, harvesting.

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Abstract

Wet corn stover harvest offers several advantages over the conventional dry harvest system. Field drying is reduced or eliminated, increasing the available harvest window. Harvesting wet stover eliminates raking, reducing cost and the chance for soil contamination. Chopping wet stover with a forage harvester would also eliminate the bale gathering, staging, and loading steps. Harvesting wet stover during grain harvest would produce a single-pass whole-plant harvesting system. These benefits are tempered by greater transport and storage costs because of lower stover density and higher moisture than dry bales. The economic potential of several different harvest and storage scenarios for single-, two-, and three-pass wet harvesting systems were evaluated. An economic analysis of a representative farm was used to estimate costs of harvest, storage, and transport to asses the most economically promising of the conceived machine configurations.

Of the physical forms considered, chopped wet stover had lower costs than billeted or baled wet stover. The low-density billets had greater transportation costs, and wet bales had additional costs associated with gathering, staging, and loading. Harvesting costs were higher when using specialized equipment such as a modified ear corn harvester or corn sheller because their use was limited to corn only, and fixed costs could not be spread over other crops. A grain combine with crop unit modified to chop and blow the stalk and leaf fraction was estimated to produce stover at \$30.8/dry Mg harvested, stored and delivered to the processing facility. This cost was \$41.9/dry Mg for a conventional system with dry bales stored outdoors, so the single-pass system was estimated to reduce costs by 25%. Two- and three-pass wet stover systems using a self-propelled forage harvester reduced delivered cost by 19 and 15%, respectively.

Background

There is increased emphasis on renewable energy and environmental sustainability by the conversion of biomass to transportation fuel, electricity, and industrial products. Alternative feedstocks such as corn stover could help meet the increased demand for renewable resources. Because of its abundance and its proximity to existing grain-to-ethanol conversion facilities, corn stover has been suggested as an ideal strategic feedstock to increase ethanol production using cellulosic conversion processes (Hettenhaus and Wooley, 2000). Compared to other biomass commodities such as switchgrass, hybrid poplars, and small-grain straw, corn stover has considerable advantages in that the grain fraction is a high value co-product and the yield of stover is quite high. Corn stover has been proposed as a feedstock for ethanol fuel production, gasification to produce electricity, or as a supplemental fiber source for paper pulp. However, there are many obstacles to the use of corn stover as a biomass feedstock. The primary obstacle is the costs associated with harvesting, handling, transporting and storing corn stover. These costs can challenge the economic viability of using corn stover as a biomass feedstock.

Current Dry Harvest System

Corn stover is typically harvested as a dry product and packaged in large round or large square bales. The current system typically involves the following steps beyond grain harvesting: shredding with flail shredder, field drying, raking into a windrow, baling, gathering bales, transporting to storage, unloading and storing. Shredding and windrowing can be combined, but this slows drying during an already difficult drying period (Schechinger and Hettenhaus, 1999; Shinners et al., 2003). Problems with this system include poor drying conditions in the Upper Midwest because of short day length and low ambient air temperatures, short harvesting window between grain harvest and snow cover, frequent weather delays, soil contamination of stover during shredding and raking, low harvesting efficiency (ratio of harvested to total stover mass), and cost. Costs of these processes have been estimated by to be in the range of $26 to 46 per dry Mg (Schechinger and Hettenhaus, 1999; Sokhansanj et al., 2002). Estimated costs for each of the operations required to harvest and transport corn stover to the storage site are provided in table 1.

Table 1. Estimated costs for various operations involved in the harvest, transport and storage of corn stover (Schechinger and Hettenhaus, 1999; Sokhansanj et al., 2002).

	Estimated cost …	$ per dry Mg
Operation	Low	High
Shred	3.5	3.7
Rake	1.3	2.0
Bale	13.5	27.2
Gather	2.0	6.5
Transport to storage site	5.5	6.7
Total	25.8	46.1

Harvesting and Storing Wet Corn Stover

Harvesting and storing wet corn stover offers many advantages over the current dry system. The most obvious advantage is that the need for field drying is reduced or eliminated, which allows harvesting soon after grain harvest. This increases the available harvest window because field drying to dry baling moisture can take from several days to weeks (Schechinger and Hettenhaus, 1999; Shinners et al., 2003). Merging stover into windrows at shredding reduced stover drying rate considerably (Schechinger and Hettenhaus, 1999; Shinners et al., 2003), so stover must be placed in wide swaths at shredding and then merged into windrows by raking before baling. Harvesting wet stover eliminates the raking operation because stover can be merged during the shredding operation, reducing cost and chances for soil contamination. Harvesting wet stover by chopping with a forage harvester would also eliminate the bale gathering, staging and loading steps.

Wet stover can be stored and preserved by several methods. Wet stover bales can be wrapped in plastic film and preserved by fermentation. This method was successfully used by Shinners et al. (2003) using both large square and round bales. Dry matter losses were quite low (less than 5% of total DM) when bale moisture was about 40%. Chopped or shredded wet stover could be stored in bunks, bags or piles and preserved by fermentation. Shinners et al. (2003) successfully ensiled stover at about 48% (w.b.) moisture in a bag silo for 7 months. Dry matter losses were not quite as low as with wrapped bales (less than 11% of total DM) probably because conditions were not as anaerobic in the bag silo. Atchison and Hettenhaus (2003) suggested wet stover could be stored in large piles where the stover is re-hydrated to 75% (w.b.) moisture similar to the sugar cane bagasse system.

Harvesting Options for Wet Corn Stover Harvesting

Corn stover can be harvested wet using existing equipment. The flail shredder can be operated right after grain harvest and be used to both shred and merge the stover. The wet stover can then be chopped with a forage harvester and ensiled in a silo or it can be baled and ensiled by wrapping the bales in plastic film. Both processes were used successfully by Shinners et al. (2003). Grain harvest, shredding/merging and chopping would be a three-pass system that would eliminate the raking and bale gathering operations of the current system. Modifications could be made to the grain harvester to eliminate all or some of the post grain harvest operations. For instance, the shredder/merger could be integrated into the combine crop unit so that the only other field operation required is chopping with the forage harvester: a two-pass system. The two- and three-pass systems have a major advantage in that existing forage harvesters have great capacity and can be used to harvest many other crops so their fixed costs can be spread over many hours of annual use. The combine crop unit could be further modified to chop and blow the leaf and stalk fraction into a container pulled alongside the grain harvester: a single-pass system with two crop streams. Further details on the machine configurations considered in this analysis are presented below.

Objectives

The specific objectives of this research were:

- To review literature to estimate the transport and storage density of different fractions of corn stover in various physical forms.

- To conceive various harvester configurations that would produce a single-pass whole-plant corn harvest with two crop streams: grain and stover.

- To conduct an economic analysis of a representative farm to estimate costs of harvest, storage, and transport to assess the most economically promising of the conceived machine configurations.

Physical Properties of Corn

No matter what process used to harvest the whole corn plant, the physical properties of the material are important because they affect type of storage, expected losses during storage and transportation costs. The following options for processing the stover fraction were considered:

- **Precision cutting** into small segments of theoretical-length-of-cut (TLC) less than 40-mm similar to a forage harvester.
- **Rough cutting or billeting** into sections of TLC from 17 to 35-cm similar to a cane harvester.
- **Baling** with or without rough size reduction.

The data below provides the bulk density of bio-mass products similar to corn stover after cutting or billeting (table 2). Jakeway (2003) reported that the bulk density of sugar cane was reduced 40% when harvested with a cane harvester at 35-cm TLC compared to harvesting with a forage harvester at 1.5-cm TLC. There is no available data concerning the bulk density of corn stover cut into billets similar to those formed with sugar cane. Based on the data by Jakeway (2003), it was assumed that billeted corn stalks would have roughly 40% lower bulk density than that of chopped stalks. Estimates of bulk density of various fractions of corn plants cut into long billets or precision cut into small pieces have been made (table 3). These data were used to estimate the transport and storage volume requirements for different harvesting and storage strategies. In these estimates, it was assumed that corn grain yield was equivalent to 9,400 kg DM/ha and stover yield was equivalent to 75% of grain mass.

Machine Configurations and Storage Options Considered

Four harvester base machines were considered. The grain combine and self-propelled forage harvester were considered as base harvesters where the crop unit could be modified to harvest corn grain and stover in two separate streams in a single pass. These machines could be used to harvest other crops using traditional crop units. An ear corn harvester and corn sheller were likewise considered for modification for single pass/two stream harvesting. These two harvester alternatives were considered because they have simpler and less expensive components than a typical combine or forage harvester. However, both harvesters would be limited to corn harvest only

A total of 16 alternative machine configurations were considered for both single- and multi-pass harvesting of corn stover (table 4, fig. 1). The grain fraction could be removed from the field as shelled and cleaned grain using the combine harvester or corn sheller. The ear corn harvester would harvest the grain as ear corn with husk and cob. The forage harvester would harvest the whole-plant with the grain intermingled with the stover, similar to corn silage. A combine crop unit could be modified to harvest the stover fraction in shredded, chopped, billeted or unprocessed physical form. For instance, the harvester crop unit could be modified to shred and windrow the stover on the ground (fig. 2), or the chopped material could be blown into a wagon or truck alongside the harvester (fig. 3).

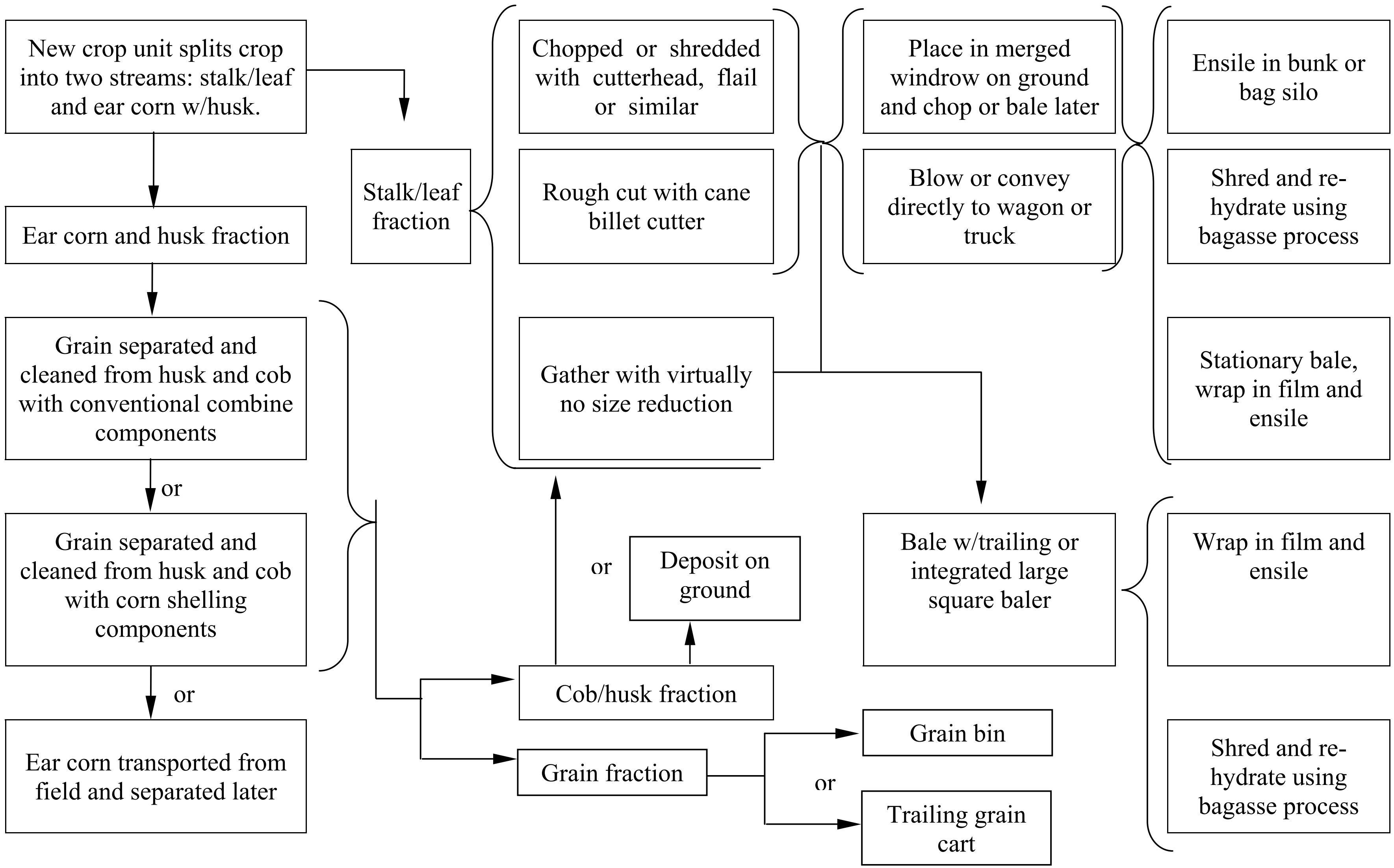
Wet stover must be preserved by fermentation to keep storage losses within reason. Ensiling stover is similar to ensiling forages for animal feed, where the two essentials are limiting oxygen and storing at proper moisture. In this analysis, two physical forms of the wet stover were considered for ensiling: chopped and placed in a silo or baled and wrapped in plastic film. Wet corn stover has been successfully ensiled using both methods (Shinners et al., 2003). Chopped material was assumed to be ensiled in a bunk, bag, or pile silo. Tower silos were not considered cost-effective for a low value product like corn stover. Bales were assumed to be wrapped in stretch plastic film using a tube wrapper (Shinners et al., 2003).

Table 4. – Machine configurations to harvest grain and corn stover and considered in the economic analysis.

Machine[&]	Harvester crop unit	Grain			Stover		
		Processing unit	Physical form	Handling	Processing unit	Physical form	Handling
1 – a and b	a – Conv. row crop b – Conv. row crop w/ flail shredder	Typical combine components	Shelled and cleaned	Grain tank	a – None b – Flail shredder	a – None b - Shredded	a – None a – Windrowed on ground
2 – a, b, and c	Conv. row crop w/ cutterhead or shredding device	a – Combine[#] b – Sheller[#] c – None	a,b – Shelled and cleaned c – Ear corn[@]	a,b – Grain tank c – Trailing wagon	Cutterhead or shredder	Chopped or shredded	Blown into truck or trailer
3 – a, b, and c	Conv. row crop w/ billeting rotors	a – Combine[#] b – Sheller[#] c – None	a,b – Shelled and cleaned c – Ear corn[@]	a,b – Grain tank c – Trailing wagon	Billeting rotor	Billeted	Conveyed into truck or trailer
4 – a, b, and c	Conv. row crop w/ gathering system	a – Combine[#] b – Sheller[#] c – None	a,b – Shelled and cleaned c – Ear corn[@]	a,b – Grain tank c – Trailing wagon	Large square baler	Baled	Bales deposited on ground
5 – a and b	a – Row crop b – Row crop w/ ear snapper	a – Chopped b – Ear corn[@]	a – Cutterhead b – None	a, b – Truck or wagon	Cutterhead	Chopped	Blown into truck or trailer
6 – a and b	a – Windrow pick-up b – Flail pick-up	–	–	–	Cutterhead	Chopped	Blown into truck or trailer
7	–	–	–	–	Large square baler	Baled	Bales deposited on ground

& - Base unit for machines 1a, 1b, 2a, 3a and 4a is a modified grain combine harvester; base unit for machines 2b, 3b and 4b is a modified corn sheller; base unit for machine 2c, 3c and 4c is a modified ear corn harvester; and base unit for machines 5 and 6 is a self-propelled forage harvester.
# - Processing units for the grain fraction are (a) conventional combine components or (b) corn sheller and cleaner.
@ - Ear corn involves snapping ear and transporting husk, cob and grain from field.

Figure 1. Process diagram for modified harvesting machines conceived to harvest corn stover in conjunction with the grain fraction.



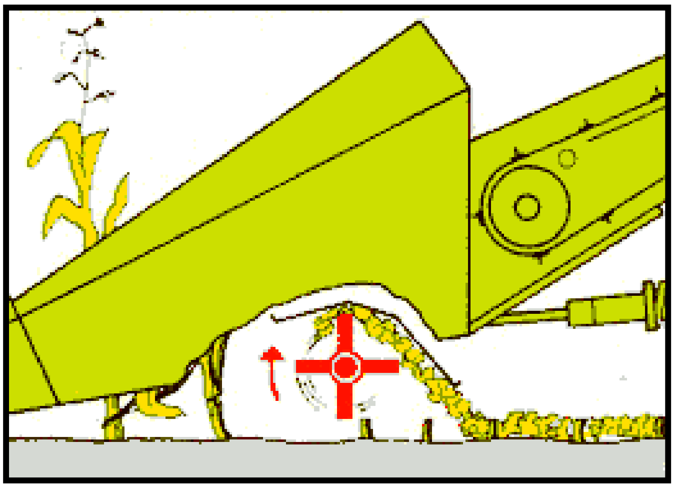


Figure 2. Modified combine crop unit used to shred and windrow stover during grain harvest.

Figure 3. Modified combine crop unit used to chop and blow leaf and stalk fraction from harvester during grain harvest.

Table 2. Approximate wet and dry bulk density of sugar cane, sorghum, corn stover, ear corn and corn cobs based on previous studies.

Product	Moisture	Density	
	% wet basis	kg WM / m^3	kg DM / m^3
Whole sugar cane[@]	65%	200	70
Bundled whole cane[@]	"	400	140
Billeted sugar cane[@]	"	350	120
Shredded sugar cane[@]	"	290	100
Billeted sorghum – 300 mm TLC[#]	65%	215	75
Chopped sorghum – 60 mm TLC[#]	"	310	110
Chopped sorghum – 6 mm TLC[#]	"	360	125
Shredded stacks of corn stover[&]	24%	60	45
Round baled corn stover[&,*]	"	135	105
Square bales corn stover[&,*]	"	190	145
Chopped corn stover[&,¤]	47%	140	75
Bagged and chopped corn stover[&,¤]	"	290	155
High moisture ear corn in field[§]	32%	625	425
Dry ear corn in crib[§]	13%	450	390
High moisture shelled corn in field[§]	28%	640	460
Dry shelled corn[§]	12%	770	675
High moisture cobs[¶]	47%	220	115
Dry corn cobs[§]	6%	165	155
Ground corn cob[§]	9%	270	245

@ – Hugot,1986
# – Monroe and Sumner, 1985
& –Shinners et al., 2003
* – Particle size of shredded corn stover was approximately 11 in.
¤ – Particle size of shredded and chopped stover was approximately 1 in.
§ – Kammel, 1991
¶ – Anderson and Bern, 1984

Table 3. Estimated yield, moisture and bulk density in transport container for various corn plant fractions.

	Yield[@]	Moisture[@]	Bulk density[#]	
	kg DM/ha	% w.b.	kg WM / m^3	kg DM / m^3
Chopped				
Whole plant	16,450	50	330	160
Stalk	4,250	72	345	95
Grain[&]	9,400	25	620	465
Cob	1,180	50	450	225
Leaves	1,120	37	80	50
Husk	500	37	80	50
All stover	7,050	65	250	90
All stover – (husk + cob)	5,370	68	250	80
Billeted				
Whole plant	16,450	50	200	100
Stalk	4,250	72	190	55
Ear corn[*]	10,580	30	615	430
Cob	1,180	50	290	145
Leaves	1,120	37	55	35
Husk	500	37	55	35
All stover	7,050	65	145	50
Stover – (husk + cob)	5,370	68	150	50
Baled				
Whole plant	16,450	50%	530	265
Stover – (husk + cob)	5,370	68%	500	160

@ – Ratios and moisture data estimated based on data from Shinners et al. (2003)

– Density estimated from data in table 2

& – Chopped grain density assumed to be approximately equal to whole grain density.

* – Ear corn consisting of grain and cob with husk removed.

Representative Farm and Economic Assumptions

A representative farm was used to make an analysis of the economic potential of the various harvesting and storage strategies considered above. The farm was assumed to harvest 400 ha of corn grain annually with an average grain yield of 9,400 kg DM/ha. The yield and moisture of the various plant fractions given in table 3 were assumed for this representative farm. In addition, it was assumed that the farm grew an additional 350 ha of small grains or soybeans that would require harvesting by a grain combine harvester. It was assumed that the average distance from the field to the storage site where stover or grain would be stored was 8 km. The distance from the storage site to the stover processing plant was assumed to be 40 km. Other assumptions made to complete the economic analysis are presented in tables 5, 6, and 7.

Table 5. Assumptions used in the economic analysis of the representative farm.

Parameter	Assumption
Labor rate	\$10/h
Fuel cost	\$0.40/L
Interest rate	8%
Inflation rate	3%
Specific fuel consumption	0.39 L/kW-h
Lubrication cost	15% of fuel cost
Taxes, insurance and housing	2% of purchase price

Fixed costs of the harvesting and transport equipment included depreciation, interest, taxes, insurance, and housing and were calculated using equations provided in ASAE Standard EP496.2 (ASAE, 2002). The fraction of the fixed costs assigned to corn harvesting was calculated based on the fraction of the total harvester operating time used for corn harvesting. Variable costs for harvesting and transporting corn grain and/or stover included labor, fuel and lubricant consumption, and repairs and maintenance. Repair and maintenance costs were calculated using ASAE Standards EP 496.2 and EP 497.4 (ASAE, 2002) using the repair factors assumed in table 7.

The transport density of the various physical forms of the corn plant (grain, whole-plant chopped, billeted stover, etc.) has a significant impact on transport timeliness and costs. Four different transport options were considered: grain cart (grain only); dump wagon (stover only); straight-frame truck, and semi-trailer truck. Machine specifications were reviewed to determine typical volumes and weight limits of the four transport machines (table 8). Weight limits were based on the lower of either the manufacturer's specification or on legal road limits. A spreadsheet was developed to calculate the average number of loads per 40 ha required to transport the whole-plant, grain, or stover from the field to the storage site (table 9). Loads could be limited by either weight or volume, although stover loads were usually limited by volume.

Table 6. – Assumed harvesting parameters for the various machine configurations considered in economic analysis.

	Machine configuration and description	Harvest speed km/h	Harvest width m	Field efficiency %	Harvested yield dry Mg / ha		Harvesting rate dry Mg / h		Annual usage h	
					Grain	Stover	Grain	Stover	Corn	Other harvesting
1a	Conventional grain combine	7.2	4.6	73	9.4	–	22.8	–	167	150
1b	Combine with shredder/merger	6.4	"	70	"	–	19.4	–	196	"
2a	Combine w/ chopper/blower crop unit	5.6	"	62	"	5.4	15.1	8.6	253	"
2b	Corn sheller w/ chopper/blower crop unit	6.1	"	"	"	"	16.3	9.3	"	"
2c	Ear harvester w/ chopper/blower crop unit	5.6	"	69	"	"	16.7	9.5	228	"
3a	Combine w/ billeting crop unit	5.6	"	62	"	"	15.1	8.6	253	0
3b	Corn sheller w/ billeting crop unit	6.1	"	"	"	"	16.3	9.3	"	"
3c	Ear harvester w/ billeting crop unit	5.6	"	69	"	"	16.7	9.5	228	"
4a	Combine w/ integrated baler	6.9	"	62	"	"	20.6	10.4	209	"
4b	Corn sheller w/ integrated baler	6.9	"	"	"	"	"	"	"	"
4c	Ear harvester w/ integrated baler	6.4	"	69	"	"	21.5	10.9	199	"
5a	SPFH w/ row-crop unit	8.1	"	70	16.4		42.5		157	250
5b	SPFH w/ ear snapper crop unit	6.9	"	62	–	5.4	20.6	10.4	209	"
6a	SPFH w/ windrow crop unit	8.1	10.9	70	–	4.6, 4.3[#]	–	33.3	65	"
6b	SPFH w/ flail crop unit	8.1	6.1	"	–	4.3	–	18.5	118	"
7	Tractor and trailed large square baler	8.1	10.9	"	–	3.9	–	30.8	71	"

- Yield was assumed to be 4.6 nd 4.3 dry Mg/ha for two- and three-pass harvesting systems, respectively.

Table 7. – Assumed purchase price, engine size, fuel use for corn harvesting and repair factors for the machine configurations considered in the for economic analysis.

Machine configuration and description		Purchase price $	Engine size kW	Harvesting fuel use L/h	Repair factors	
					RF_1	RF_2
1a	Conventional grain combine	$195,000	240	95	0.040	2.10
1b	Combine with shredder/merger	$205,000	280	105	0.041	2.11
2a	Combine w/ chopper/blower crop unit	$215,000	315	125	0.045	2.15
2b	Corn sheller w/ chopper/blower crop unit	$205,000	"	"	0.040	2.10
2c	Ear harvester w/ chopper/blower crop unit	$195,000	260	105	0.040	2.05
3a	Combine w/ billeting crop unit	$205,000	300	120	0.045	2.15
3b	Corn sheller w/ billeting crop unit	$195,000	"	"	0.040	2.10
3c	Ear harvester w/ billeting crop unit	$185,000	250	100	0.040	2.05
4a	Combine w/ integrated baler	$255,000	300	120	0.055	2.15
4b	Corn sheller w/ integrated baler	$245,000	"	"	0.050	2.10
4c	Ear harvester w/ integrated baler	$235,000	250	100	0.055	2.15
5a	SPFH w/ row-crop unit	$295,000	410	160	0.030	1.80
5b	SPFH w/ ear snapper crop unit	$310,000	"	"	0.030	1.80
6a	SPFH w/ windrow crop unit	$295,000	"	"	0.030	1.80
6b	SPFH w/ flail crop unit	$310,000	"	"	0.030	1.80
7	Tractor and	$100,000	150	60	0.007	2.00
	trailed large square baler	$85,000	–	–	0.150	1.90

Estimates of the purchase price were made using typical retail list prices for power units and containers to determine transport costs. Annual fixed costs were assumed to be 12 or 14% of the power unit or container purchase price, respectively. Transport fuel use rate was estimated based on power-unit engine size. Repair costs per hour were estimated at 0.02 and 0.04% of the inflation adjusted purchase price for the power unit and container, respectively. Total transport time was based on assumed speeds that could be achieved in the field and on the road, the number of trips required and the assumed round trip distance from the field to the storage site. Maximum road speed was assumed to be 25 and 70 km/h for tractors and trucks, respectively. Labor costs for transport were determined from the total transport time and the prevailing labor rate (table 5). Transport costs were calculated per unit product dry-mass.

Table 8. Assumed transport volume or weight limits based on typical manufacturers' specifications and legal weight limits.

	Grain cart*	Dump wagon#	Straight-frame truck	Semi-trailer truck	Rail boxcar	Rail gondola car
Maximum container volume .. m^3	30	23	46	89	187	315
Maximum product weight .. kg	19,500	10,200	13,600	22,000	72,500	90,800

* - Used to transport grain only. # - Used to transport stover or ear corn only.

Stover Storage Costs

Costs for storing stover at the storage site were estimated using a spreadsheet model developed by Holmes and Franks (2003) which is used to estimate the investment and annual costs of storing forages in both wet and dry form. The number of assumptions and inputs needed for this model are too great to report all here. Major assumptions are presented in table 10. Among the major costs estimated in the model are those for excavation and gravel fill, structures, loading, packing (where appropriate), covering with plastic and tires (where appropriate), and unloading. The model is iterative so that building or silo length, width or height can be optimized to return the lowest storage cost for the amount of product to be stored. Facility costs associated with storing bales outdoors, wrapped silage bales or pile silo were for excavating and creating a gravel pad to facilitate drainage and product removal during inclement weather. Facility costs for dry bales stored indoors were for a typical open-front hay-storage building. Facility costs for the bunk silo was for a concrete pad with walls. Plastic disposal cost was not included in any of the storage options that used a plastic cover.

Transport from Storage to Processing Site

Two options were considered for transporting stover from the storage site to the processing facility: by semi-trailer truck or by railcar. Only chopped or baled stover were considered in this analysis because billeting was not considered a viable harvest option (see results below). It was assumed that it would not be cost effective to remove stover from storage at the farmstead, truck it to a rail site and then transfer it to a rail car. Therefore, it was assumed that if rail transport were to be used, stover would have be stored at a rural, centralized location, such as a grain storage cooperative, adjacent to a rail siding where the stover could be loaded directly onto rail cars during removal from storage. Baled stover would be transported using flatbed truck trailers or rail boxcars. Chopped stover would be transported using commodity truck-trailers or gondola rail cars. The shipping distance from the storage site to the processing facility was assumed to be 40 km and the shipping costs for rail and truck transport were assumed to be \$0.02 and 0.08 per Mg-km, respectively, based on estimates by Souleyrette (1998).

Table 9. Average number of loads required per 40 ha of corn based on the assumed density and moisture of the various fractions given in table 3 and transport vehicle volume or weight limits given in table 8.

	Bulk density	Moisture	Number of loads per 40 ha		
	kg WM / m^3	% w.b.	Grain cart* / Dump wagon	Straight-frame truck	Semi-trailer truck
Whole-plant					
Billeted	200	50	286	143	75
Chopped	330	"	174	98#	61#
Baled	530	"	–	98	61#
Grain fraction					
Shelled	620	25	30#	37#	23#
Ear corn	615	30	64#	45#	28#
Wet stover fraction					
Billeted@	150	67	195	100	51
Chopped@	250	"	117	60	32
Baled@	500	"	–	49#	31#
Chopped¶	220	60	96	50	25
Baled¶	400	"	–	33#	20#
Dry stover fraction					
Baled¶	200	20	–	21	11

* – Grain cart used for shelled grain only.

\# – Load limited by maximum permissible weight, otherwise load limited by container volume.

@ – Leaf and stalk fractions only, cob and husk left on field or harvested with ear corn.

¶ - Two or three pass system where yield of leaf, stalk, husk and cob fractions was assumed to be 55 and 60% for the baled and chopped systems, respectively.

Table 10. Major assumptions used to estimate stover storage costs using spreadsheet model developed by Holmes and Franks (2003).

	DM loss in storage	Storage density	Storage facility cost
	% of total	kg DM / m^3	\$ per m^2
Dry stover bales			
Stored indoors	**7**	144	64.5
Stored outdoors	15	144	5.4
Wet stover bales			
Wrapped silage bales	5	160	5.4
Wet chopped stover			
Bunker silo	12	160	16.1
Bag silo	10	160	5.4
Pile silo	15	144	5.4

Results

Selected costs of harvesting and transporting corn grain and stover are reported in table 11/ The cost of grain harvest alone at \$74/ha for the representative farm, which compares favorably with the range of \$47 to 82/ha (average \$60/ha) charged by custom harvesters in Iowa (Anon., 2003). The model also estimated average grain hauling costs for the representative farm of \$32/ha, which also compares favorably with the range of \$17 to \$61/ha (average of \$29/ha) for custom hauling in Iowa. The model estimated the cost to shred, rake, bale, and gather dry stover bales at \$81/ha, which was slightly higher than the \$70/ha estimated by Sokhansanj et al. (2002) but considerably lower than \$103/ha estimated by Schechinger and Hettenhaus (1999). The estimated transportation cost of dry stover bales was \$40/ha, similar to that of \$35/ha estimated by Sokhansanj et al. (2002). Therefore, the total estimated cost on the representative farm for the current multi-pass harvesting and transport system of grain and stover was \$227/ha, not including storage costs.

The lower cost assumed for the corn sheller or ear corn harvester was more than offset by the fact that these machines were limited to corn harvesting only, so their fixed costs were not diluted over other harvesting operations. For instance, the ear corn harvester with crop unit modified to chop the stover fractions was considered to have a \$20,000 lower purchase price than a similarly modified grain combine (table 7). However, the total harvesting and transport costs were higher by \$8/ha because of higher fixed costs per hour and higher transport costs associated with hauling ear corn instead of shelled corn. Ear corn would require another process on the farm to separate the grain, the cost of which was not included in the analysis. Cobs collected from the separation process could add additional income to help the economic return of this harvesting option.

The addition of an integral or trailed baler with a combine, sheller, or ear corn harvester was also not cost effective (table 11). These configurations had higher fixed and variable costs from the higher purchase price than other machine options (table 7) and also suffered from the extra costs associated with gathering, staging, and loading bales. These additional operations added $6.8/ dry Mg to the stover transport costs compared to chopped material. Billeting was assumed to be a slightly less expensive process than chopping (table 7) so billeting harvest costs were about $0.7/dry Mg less. However, low billet density increased transport effort (table 9) so the transport costs to the storage site were about $1.7/dry Mg greater than chopped stover, so total costs for harvesting and transporting in billets were about $1.0/ dry Mg greater. Additional disadvantages of the billet or bale systems are that additional steps, such as wrapping bales in film or shredding for storing in a silo would be required. Based on this analysis, systems that field chop the material not only produced the required physical form for ensiling and downstream processing, but were the lowest cost of the options considered. Therefore, chopping was the only process considered for the remainder of the analysis.

The most cost-effective single-pass harvester was the self-propelled forage harvester, which had 40% lower costs per ha than the conventional system (table 11). The forage harvester has high capacity and can be used to harvest many crops throughout the year, so its considerable fixed costs can be well diluted. However, the $138/ha total cost does not include the additional process required to separate the grain from the stover. Hydrodynamic separation of grain and stover was not successful for wet whole-plant corn (Savoie et al., 2003). Additionally, the grain fraction would incur considerable damage during chopping. Although this machine has many advantages in terms of capacity and low harvesting cost, these additional negative factors reduce the attractiveness of this process.

The most promising single-pass harvester involved the modification of the combine crop unit to chop and blow the stover fraction (fig. 3). The harvesting and transport costs of this process were 20% less than that of the conventional system (table 11). The two-pass and three-pass systems were also quite cost effective, reducing cost of stover harvest and transport by 18 and 17%, respectively. Both systems are cost effective because the forage harvester can be used for harvesting many other crops throughout the year so its fixed costs are well diluted. These two systems do have the disadvantage of requiring additional passes, which would result in additional timeliness costs that are not accounted for in the analysis. These two systems would also result in lower harvesting efficiency and greater chance of soil contamination than a single-pass system. The incremental cost beyond grain harvest and transport for harvesting and transporting stover to the storage site was estimated to be $30.9, 14.2, 17.4 and 19.0 per dry Mg stover, for the conventional, single-, two-, and three-pass, systems, respectively (table 11).

The most cost effective storage method for wet stover would be in a bag silo or as wrapped silage bales (table 12) because dry matter losses were assumed to be the lowest for these methods (table 10). Storage costs for these two options were slightly less than storing dry stover bales indoors, but about 50% greater than storing dry bales outdoors. This is a major disadvantage of the wet stover system. The other major disadvantage of the wet stover system is that transportation costs from the storage to processing site are about twice those of the dry stover system (table 12). The results show that rail transport is the most viable option for shipping wet stover.

Table 11. Costs of harvesting and transporting grain and corn stover for selected harvester configurations.

	Harvest costs $/dry Mg	Transportation cost from field to storage site $/dry Mg		Harvest and total (harvest + transport) cost for grain + stover $/ha	
		Grain	Stover	Harvest	Total
Conventional system					
Combine grain*	7.8	3.5	–	74	106
Dry stover baling@	20.6	–	10.2¶	81	121
Total				155	227
Single-pass systems					
Whole-plant w/ SPFH#	4.8	3.6		79	138
Combine w/ chopper crop unit^	7.5	3.5	7.0	111	182
Combine w/ integral baler	7.5	3.5	13.8	111	219
Ear corn harvester w/ chopper crop unit	6.6	4.4	7.0	105	190
Two-pass system					
Combine w/ crop unit to shred & merge stover	9.1	3.5	–	86	119
SPFH chopping stover windrow&	7.4	–	7.3	34	67
Total				111	186
Three-pass system					
Combine grain	7.8	3.5	–	74	106
Shredding and merging	4.4	–	–	17	17
SPFH chopping stover windrow&	7.6	–	7.4	32	64
Total				121	187

* – Grain yield assumed to be 9.4 dry Mg/ ha.

¶ - Includes costs for gathering, staging and loading bales which accounts for $5.5 per dry Mg.

@ - Harvest stover yield assumed to be 3.92 dry Mg/ha for conventional multi-pass system and dry storage.

^ - Harvested stover yield assumed to be 5.37 dry Mg/ha for single-pass system and wet storage.

– Requires additional grain separation operation not included in total cost.

& –Harvested stover yield assumed to be 4.59 and 4.26 dry Mg/ ha for two- and three-pass systems, respectively, with wet storage.

The total cost to harvest, store, and transport was estimated to be $47.3 and 41.9 per dry Mg for conventional method of dry bales stored indoors and outdoors, respectively (table 13). The cost of the single-pass system using a combine with modified crop unit that chops the leaf and stalk fractions was $30.8 per dry Mg, or a reduction of 26% from dry bales stored outdoors. Harvesting costs were 54% less, but storage and transport costs were 50% greater for the single-pass wet stover system compared to the dry bales stored outdoors. The total costs for the two- and three-pass wet systems were 19 and 15% less than the dry bales stored outdoors. Any of the wet stover harvesting systems would greatly improve timeliness and reduce soil contamination of the stover, and the economic impact associated with these benefits would only enhance the reduction in costs found here.

Table 12. Estimated costs for loading, storing, unloading, and transporting corn stover for various harvesting and storage systems.

	Loading, storage, and unloading costs $ / dry Mg	Transport cost from storage site to processing facility $ / dry Mg		Number of trucks or railcars delivered processing facility per 1000 dry Mg stover	
		Truck	Rail	Truck	Rail
Dry stover bales					
Stored indoors	15.4	4.1	1.1	72	36
Stored outdoors	10.0				
Wet stover bales					
Wrapped silage bales	14.6	8.3	2.1	110	43
Wet chopped stover					
Bunker silo	17.7	8.3	2.1	110	43
Bag silo	14.5				
Pile silo	17.7				

Table 13. Total cost per unit dry mass of stover delivered to processing site located 40 km from storage site.

	Harvest and transport to storage site	Loading, storage and unloading	Transportation to processing facility	Total
	$ per dry Mg delivered			
Dry stover bales				
Stored indoors	30.9	15.4	1.1	47.3
Stored outdoors	"	10.0	"	41.9
Wet stover bales				
Wrapped silage bales	28.5	14.6	2.1	45.2
Wet chopped stover				
Single-pass	14.2	14.5	2.1	30.8
Two-pass	17.4	"	"	34.0
Three-pass	19.0	"	"	35.6

Conclusions

Compared to the conventional multi-pass dry stover bale system, wet stover harvesting can eliminate several field operations, all but eliminate field drying, increase the harvesting window, improve timeliness, and reduce stover soil contamination. These benefits are tempered by greater transport and storage costs because of lower density and higher moisture. Of the physical forms considered, chopped wet stover had lower costs than billeted or baled wet stover. The low-density billets had greater transportation costs, and wet bales had additional costs associated with gathering, staging and loading. Harvesting costs were higher when using specialized equipment such as modified ear corn harvesters or corn shellers because their use was limited to corn only, and fixed costs could not be spread over other crops. A grain combine with crop unit modified to chop and blow the stalk and leaf fraction was estimated to produce stover at $30.8/dry Mg harvested, stored and delivered to the processing facility. This cost was $41.9/dry Mg for a conventional system with dry bales stored outdoors, so the single-pass system was estimated to reduce costs by 26%. Two- and three-pass wet stover systems using a self-propelled forage harvester reduced delivered cost by 19 and 15%, respectively.

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