SINGLE-PASS, SPLIT-STREAM HARVEST OF CORN GRAIN AND STOVER

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ABSTRACT. *A grain combine was equipped with a whole-plant corn head and modified to produce single-pass, whole-plant corn harvesting with two crop streams: grain and stover. Capture of potential stover DM varied from 48% to 89% for leaves, from 49% to 92% for stalks, and was greater than 90% for husks and cobs, depending on corn head height. Stover aggregate moisture varied between 36% and 50% (w.b.), and area capacity ranged between 1.6 and 2.6 ha h^{-1}, depending on corn head height. Whole-plant harvesting reduced area capacity by nearly 50% compared to harvesting with a conventional ear-snapping head. Single-pass stover had an average particle size of 69 mm and bulk densities of 51 and 110 kg DM m^{-3} in the wagon and bag silo, respectively. Estimated ethanol yield ranged between 2600 and 3945 L ha^{-1}, depending on corn head height. Fermentation of single-pass stover in a bag silo was adequate, with average losses of 6% of total DM.*

Keywords. *Biomass, Biomass collection, Biomass harvest, Corn grain, Corn stover, Density, Particle size.*

Corn stover is the non-grain portion of the plant and consists of the stalk, leaf, cob, and husk fractions. Corn stover has the greatest potential as a biomass feedstock in North America, with potential annual yields of 130 Tg producing 38.4 GL of bioethanol (Kim and Dale, 2003). 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 corn stover is quite high. The primary obstacles to the widespread adoption of corn stover as a biomass feedstock are the costs associated with harvesting, handling, transporting, and storing corn stover.

Corn stover has been harvested as supplemental feed for beef and non-lactating dairy animals for decades and today 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 a 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 (Shinners et al., 2007b). Problems with this system include poor drying conditions in the Upper Midwest due to short day length and low ambient air temperatures, a 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 available stover mass), and high cost.

Harvesting and storing wet corn stover virtually eliminates the need for field drying, which allows stover harvesting soon after grain harvest. 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 also eliminates the bale gathering, staging, and loading operations. Chopped or shredded wet stover could be stored in bunks, bags, or piles and preserved by fermentation. Losses of wet stover ensiled at 44% moisture averaged 3.9% of total DM with low production of typical forage fermentation products (Shinners et al., 2007b). The current wet stover system is a three-pass system involving grain harvest, shredding/merging, and chopping. Modifications could be made to the grain harvester to eliminate all or some of the post-grain harvest operations currently used to harvest stover. For instance, a device to shred and merge the stalks and leaves could be integrated into the combine corn head so that the only other field operation required is chopping with the forage harvester, a two-pass system. 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. An alternative single-pass system is to adopt a whole-plant corn head from a forage harvester to the grain combine and collect the non-grain fraction that exits the rear of the harvester. A grain combine with crop unit modified to chop and blow the stalk and leaf fraction was estimated to produce stover at $30.8 per dry Mg harvested, stored, and delivered to the processing facility (Shinners et al., 2003). This cost was $41.9 per dry Mg for a conventional system with dry bales stored outdoors, so the single-pass sys-

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tem was estimated to reduce costs by 26%. Two-pass and three-pass wet stover systems using a self-propelled forage harvester reduced delivered cost by 19% and 15%, respectively.

Research work was carried out in the 1960s and 1970s looking at the feasibility of simultaneous harvesting of corn grain and stover (Albert and Stephens, 1969; Ayres and Buchele, 1971, 1976; Buchele, 1976; Hitzhusen et al., 1970; Schroeder and Buchele, 1969). These machines typically size-reduced the stover using a chopping cylinder, and transported it using an impeller-blower. Some machines handled the grain fraction as ear corn, while others threshed and separated the grain at harvest. Some separated and processed the stalk and leaf fractions before they went to the threshing or husking systems, while others size-reduced the whole-plant prior to sending all the material to the threshing and separation systems. Many of these machines were small, harvesting only one or two rows. They were also single-use, dedicated to corn harvest only. Shinners et al. (2003) reported that the most economical method of single-pass stover and grain harvest was to make modifications to the existing grain combine harvester so that fixed costs of the harvester can be diluted over other harvesting operations.

The objectives of this research were (1) to modify a large-capacity grain combine to harvest the whole-plant in a single-pass while creating two separate crop streams (grain and stover), (2) to quantify the performance of the modified harvester, (3) to quantify the storage characteristics of the ensiled stover, and (4) to estimate the chemical composition and ethanol yield of the harvested stover fractions using near-infrared spectroscopy (NIRS).

Materials and Methods

Machine Description

Two modifications were made to a John Deere model 9760 combine so that single-pass, split-stream harvesting could be investigated (fig. 1). First, a John Deere model 666R forage harvester whole-plant corn head was adapted to the combine harvester to simultaneously capture the stover and grain fractions. The addition of several sawtooth feeding paddles to the gathering auger was the only modifications needed to produce satisfactory feeding to the combine feeder house. Second, a flail chopper, cylindrical blower, and spout were added to the rear discharge of the combine to size reduce and convey the non-grain fractions to a trailing wagon. The flail chopper rotor operated at 2500 rpm, was 1310 mm wide, and had 30 pairs of hammers distributed on four rows. The hammers dragged material past 29 stationary knives, where size reduction took place. The theoretical length of cut (i.e., the lateral spacing between the knives) was 45 mm. Material discharged from the chopper was expelled to a cylindrical blower mounted 1.4 m from the chopper exit. The 450 mm diameter blower was 510 mm wide, had 12 paddles, and was belt driven at 1800 rpm. Material was discharged from the blower into a forage harvester spout that concentrated the crop stream, directing the stream to the trailing wagon. The Miller Pro model 7012 side-dumping wagon was equipped with load cells to determine the weight of the contents. Performance of the modified system was quite good. Crop fed well from the whole-plant head to the feeder house, and no difficulties were encountered with material flow through the chopper, blower, or spout.

Figure 1. Modified grain combine producing single-pass, split-stream harvest of corn grain and stover (photo courtesy of Wolfgang Hoffman).

Quantifying Machine Performance

A replicated-block field experiment was conducted to quantify the performance of the modified harvester. Tests were conducted on 3 to 5 November 2004 at the Arlington Agricultural Research Station of the University of Wisconsin using a typical corn variety intended for grain production (table 1). Four treatments were explored: the whole-plant corn head operated at approximately 125, 530, and 760 mm stubble height, plus a control treatment of a conventional ear-snapper head operating right below the hanging ear level. Maximum harvest height with either head was limited by the lowest position of the hanging ears. Several rounds were made around the field to remove the field edges and headlands. The field was then separated into 12 plots of 150 m length by 4.6 m width. Three replicate tests were conducted per treatment, and the four treatments and replicates were randomly assigned to the 12 plots.

Prior to harvest, plant population was determined by counting the number of viable plants in six random 5.3 m test strips in each plot. The number of lodged plants, lodge height, erect plant height, and ear height were also determined in each strip. A 1.61 m^2 grid was then placed in three random locations within each plot. Corn crop lying on the ground prior to harvest was gathered and separated into one of five fractions: stalk, leaf, husk, cob, or grain. Each of the five fractions was weighed, oven-dried at 103° C for 24 h, and then the dry mass was determined. The plants within the grid were cut right above the first node and separated into the same fractions mentioned above. The stalk was further subdivided into quarters by nodes and identified as bottom (1st to 5th nodes), mid-bottom (5th to 9th nodes), mid-top (9th to 13th nodes), and top (>13th nodes) fractions (Shinners et al., 2007a). For two of the grids, all eight fractions were weighed and oven-dried as described above. The fractions from the third grid were intended for chemical composition analysis (see below) and were dried at 65° C for 72 h.

After pre-harvest data collection, the harvester was used to harvest the plots. Ground speed was altered with the harvester hydrostatic transmission so that engine speed was maintained at approximately 2260 rpm in an attempt to maintain similar harvester loading between treatments. Threshing cylinder speed was maintained at 300 rpm and cleaning fan speed at 920 rpm. Time to harvest the plot was recorded so that ground speed, stover mass flow, and grain mass flow could be calculated. Stubble height was measured in six random grid locations in each harvested plot. The mass of stover harvested was determined by weighing the wagon contents to the nearest 2 kg. The volume of the stover in the wagon was estimated by leveling the load by hand and recording the height of the material in the container. Load density was determined by diving load mass by volume. The plot length was chosen so that a nearly full wagon was produced after each test run. Several random grab samples were collected from each load. Three subsamples were used to determine stover moisture by oven-drying for 24 h at 103°C. Three additional samples were collected to determine chemical composition (see below), so they were dried at 65°C for 72 h. An additional two samples were collected for particle-size analysis using procedures described in ASAE Standard S424.1 (*ASAE Standards*, 2007). The harvester grain tank was unloaded, and the grain weight was determined to the nearest 2 kg. Several subsamples were collected to determine grain moisture by drying at 103° C for 24 h.

Table 1. Characteristics of crop used in quantifying the machine performance of the single-pass stover and grain harvester.

Variety	Pioneer 35R58
General relative maturity (GRM)	105 days
Planting date	29 April 2004
Harvest dates	3 to 5 Nov. 2004
Ear height (mm)	1,213
Standing height (mm)	2,683
Plant population (plants ha^{-1})	73,688
Pre-harvest loss (Mg DM ha^{-1})	0.44 leaf, 0.12 stalk

Differences between treatments were analyzed using analysis of variance, and statistical differences were determined using a least significant difference (LSD) test at the 90% or 95% probability level. The main variable in this study was cut height of the whole-plant corn head. This parameter was quantified by the average stubble height after harvest and expressed as a dimensionless ratio of the cut height to the average plant ear height. Performance parameters of interest were plotted as a function of this ratio, and regression analysis was performed. The regression analysis was carried out using only the data collected while using the whole-plant corn head, not the ear-snapper head. The R^2 values reported in the plots reflect only the data collected with the whole-plant head.

Stover Chemical Composition

The chemical composition of the pre-harvest stover fractions (cob, husk, leaf, and stalk by section) and the aggregate harvested stover was determined analytically using NIRS. The collected spectra were used to estimate chemical composition using the “Stover9” calibration developed by Hames et al. (2003). After oven-drying (see above), samples for analysis were ground in a conventional laboratory hammer mill equipped with a 2 mm screen. The samples were scanned using a Foss NIR Systems model 6500 forage analyzer with a standard reflectance detector array. The spectral analyzer used two silicon detectors to monitor visible light from 400 to 850 nm and four lead-sulfide detectors to monitor NIR light from 850 to 2500 nm. Each sample was split into three replicate subsamples and packed in conventional 60 mL sample cells. For each cell, 32 spectra were collected and averaged, and a reference scan was conducted before and after each cell. Spectra were sent to NREL for analysis using the Stover9 calibration.

Storing Wet Stover

Three separate fields of about 3 ha each were harvested on 11 and 12 November 2004 with the modified harvester, and the harvested stover was ensiled. Three corn varieties were used: a typical grain hybrid (Pioneer 35R58), a silage leafy hybrid (Northup King N48-V8), and a low-lignin silage variety (Mycogen F697). The modified harvester was operated as described above with the whole-plant corn head set to produce a stubble height of approximately 25 cm. The harvested material was stored in 3 m diameter plastic silo bags. The location of each load was marked on the bag, and later the length and diameter of the bag at each load was determined so that silo density could be calculated using the load mass. Prior to storage, three subsamples per load were collected for moisture and particle-size determination using the techniques described above.

The silo bags were opened on 22 June 2005 after about eight months in storage. The stover was removed with a loader, and spillage was hand-collected to minimize take-out losses. Each load was weighed to the nearest 2 kg. Three subsamples were taken at each load location and oven-dried at 65°C for 72 h for moisture determination. An additional sample was collected from each load location and oven-dried at 65°C, hammer-milled to 2 mm particle size, and then analyzed for ash content, nitrogen, acid detergent fiber (ADF), and neutral detergent fiber (NDF) using standard wet laboratory analysis techniques. A final sample from each load location was collected, frozen, and analyzed for fermentation products (lactic acid, acetic acid, and pH) through the use of high-performance liquid chromatography (HPLC).

Table 2. Fractional yield of the standing corn crop prior to harvest.

	Yield (Mg ha^{-1})		Fraction of Stover (%)		
	DM	Water	DM	Water	Moisture (% w.b.)
Bottom stalk	2.16	5.32	22.6	56.9	71.1
Mid-bottom stalk	1.88	1.65	19.6	17.6	46.8
Mid-top stalk	0.75	0.22	7.9	2.4	22.7
Top stalk	0.13	0.05	1.4	0.6	28.4
Total stalk	4.93	7.31	51.5	78.2	59.7
Cob	1.85	0.35	19.3	3.7	15.8
Husk	1.08	0.38	11.3	4.1	26.1
Leaf	1.72	1.25	18.0	13.3	42.0
Stover	9.57	9.35			49.4
Grain	10.49	3.19			23.3
Whole plant	20.07	12.51			38.4

Results

Machine Operation

Crop characteristics just prior to harvest were considered typical for this variety (Pioneer 35R58) and location (Shinners et al., 2007a). At the time of harvest, the stalk made up over 50% of the total DM of the stover fraction and contained more than 75% of the available water in the stover (table 2). The bottom quarter of the stalk contained almost 25% of the stover DM and more than 50% of the stover water. The cob, husk, and top half of the stalk made up about 40% of the stover DM but contained less than 11% of the available water in the stover.

Using the whole-plant corn head, the fraction of total stover DM harvested varied nearly linearly with cut height (fig. 2). The whole-plant head harvested greater than 90% of the cob and husk regardless of cut height (table 3). The ear-snapper head also harvested greater than 90% of the cob, but significantly less of the husk because the snapper rolls tended to strip the husk from the cob and eject it below the head (table 3). The fraction of leaf and stalk harvested were also well correlated with cut height (fig. 3). At harvest, the leaves had drooped, so at the two highest cut heights, leaves were cut by the stalk cutoff disks and were lost. The ear-snapper head harvested less than 25% of either the leaf or the stalk when set at typical operating height (table 3). The fraction of grain captured in the combine bin was greater than 99% for the two lowest cut heights (table 3). The cobs had drooped by harvest, so cut height of the whole-plant head was limited to 63% of ear height to reduce grain loss. Nonetheless, an occasional ear was sheared at that cut height, so grain loss was very high at that cut height (table 3). Grain loss was less than 1% for all other operating conditions, and less than 2% of the total grain yield was located in the stover fraction for all operating conditions (table 3).

Aggregate stover moisture was linearly correlated with the ratio of cut height to ear height for the whole-plant corn head (fig. 4). The top half of the stalk, husk, and leaves were all less than 30% moisture at harvest, so the high cut height or use of the ear-snapper head resulted in poor capture of the moisture in the stalk and overall low aggregate moisture. Harvested stover moisture was greater than 50% only when the whole-plant head was set to capture the bottom section of the stalk (table 3). The whole-plant head was able to capture from 50% to 90% of the available stover moisture, depending on cut height (fig. 5). The storage scheme envisioned for direct-harvested stover involves preservation by ensiling, and moisture is needed for adequate preservation. Chopped

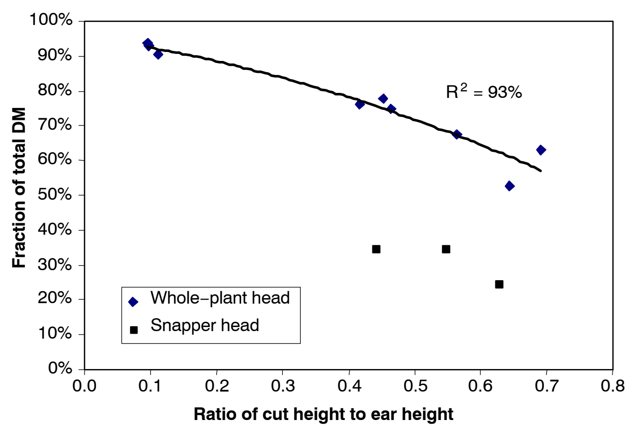

Figure 2. Fraction of total stover DM harvested as a function of cut height for the whole-plant corn head and conventional snapper head.

Table 3. Fraction of total standing stover DM and grain DM harvested as a function of head height for the whole-plant corn head and conventional snapper head.[a]

Head Type	Ratio of Head to Ear Height	Fraction of Standing Stover DM Harvested: Cob	Husk	Leaf	Stalk	Stover	Aggregate Stover Moisture (% w.b.)	Fraction of Grain DM: Lost	In Grain Bin	In Stover Wagon
Whole−plant	0.10	97.7 b	96.5 b	89.1 c	92.3 d	93.1 c	50.2 c	0.3 a	99.1 b	0.6
Whole−plant	0.44	96.3 ab	95.8 b	71.9 c	69.5 c	78.3 b	43.1 b	0.4 a	99.2 b	0.4
Whole−plant	0.63	91.0 a	94.7 b	47.6 b	48.5 b	62.5 b	36.4 b	6.8 b	91.9 a	1.3
Snapper	0.54	97.0 ab	52.5 a	24.0 a	13.9 a	36.2 a	25.4 a	0.8 a	97.7 b	1.5
LSD (P = 0.10)		6.0	17.2	19.9	6.1	8.3	3.9	5.3	5.5	1.1

[a] Values in the same column followed by different letters are significantly different at the 90% confidence level.

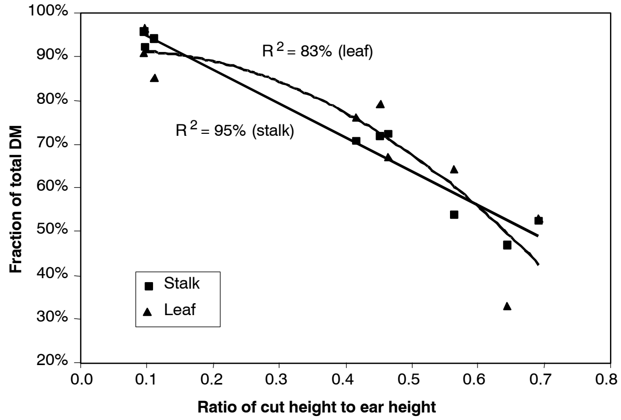

Figure 3. Fraction of total stalk or leaf DM harvested as a function of cut height for the whole-plant head only.

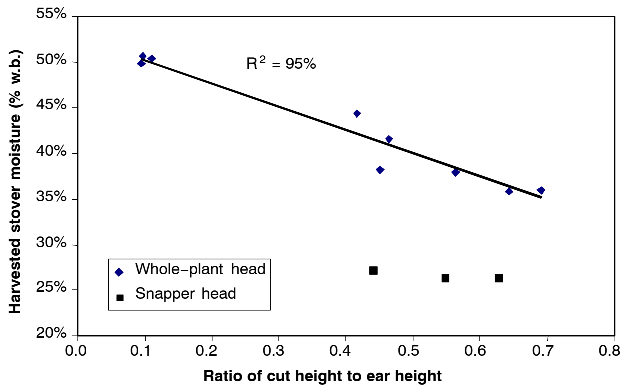

Figure 4. Moisture content of the aggregate stover harvested as a function of cut height for the whole-plant corn head and conventional snapper head.

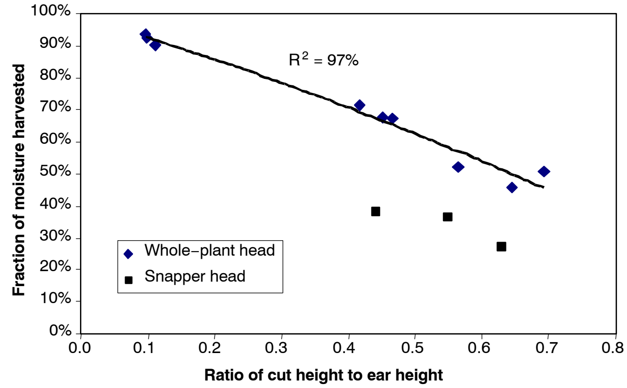

Figure 5. Fraction of water available in total stover as a function of cut height for the whole-plant corn head and conventional snapper head.

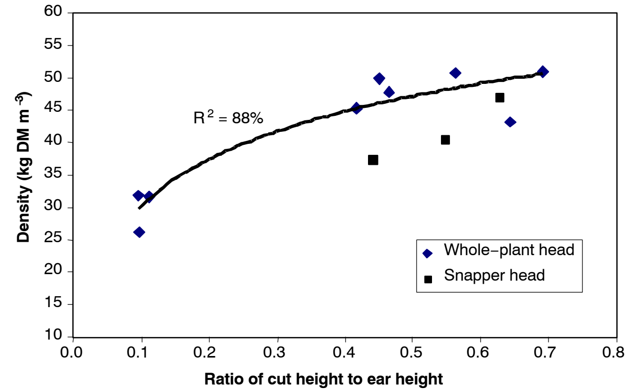

Figure 6. Dry bulk density of aggregate harvested stover as a function of cut height for the whole-plant corn head and conventional snapper head.

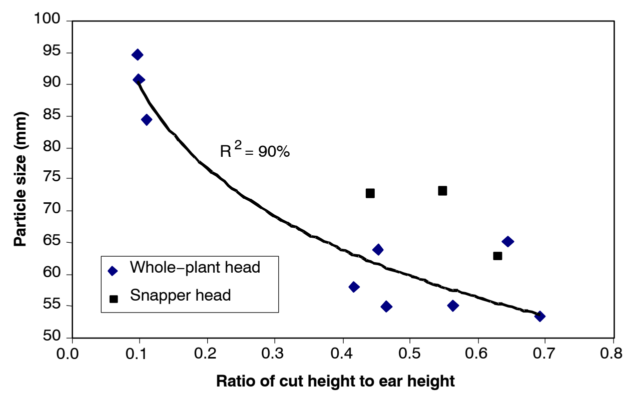

Figure 7. Aggregate stover particle size as a function of cut height for the whole-plant corn head and conventional snapper head.

stover ensiled in a bag silo was well preserved for 12 months at moistures as low as 42% (Shinners et al., 2007b), so it appears that the two lowest cut heights would provide adequate stover moisture. It is unknown how well stover harvested with the ear-snapper head would be preserved, given the low moisture of the aggregate.

Forage density is a function of particle size and particle density. Precision-cut forage harvesters have a set of feedrolls that meter the material into a cutterhead, so when whole-plant corn silage is reasonably aligned with the cutterhead, the differences between actual and theoretical length of cut (ALC and TLC, respectively) are small (Shinners, 2003). Density of whole-plant corn silage has been reported to range from 90 to 125 kg DM m^{-3} (van der Werf and Muller, 1994; Wiersma and Holmes, 2004). Stover harvested by shredding, windrowing, and chopping with a precision-cut forage harvester was not well aligned in the feedrolls, so when the TLC was 13 mm, the ALC was about 24 mm and density in the truck was only 71 kg DM m^{-3} (Shinners et al., 2007b). Chopped stover density was lower than whole-plant density because chopped stover lacked the high-density grain fraction and because its particle size was quite long. In this study, the stover density in the wagon was no greater than 51 kg DM m^{-3} (fig. 6). The average particle size independent of the cut height was 69 mm (fig. 7). The stover particle size was well correlated with the cut height ratio, and bulk density was well correlated with stover particle size (figs. 7 and 8). Stover size reduction occurred from the shredding that took place in the threshing and separation cylinder and in the flail chopper at the harvester discharge. Longer particle size resulted when more of the bottom of the stalk was harvested. The bottom of the stalk was higher in lignin and mechanically stronger than other parts of the plant, so it was more difficult to shred. In addition, the stover could not be well oriented for cutting in the flail chopper. Typical Midwest road regulations restrict shipping volume and weight, constraining stover transport density to a maximum of about 240 kg WM m^{-3}. In this study, wet stover density averaged 73 kg WM m^{-3}, well short of the desired target. Machine systems that produce smaller particle size will be needed to achieve the required transport density.

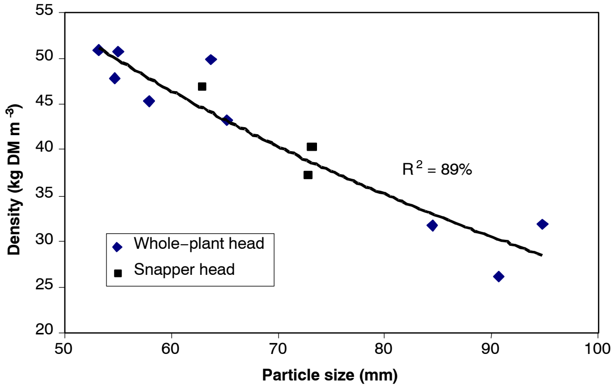

Figure 8. Dry bulk density of the aggregate stover as a function of particle-size for the whole-plant corn head and conventional snapper head.

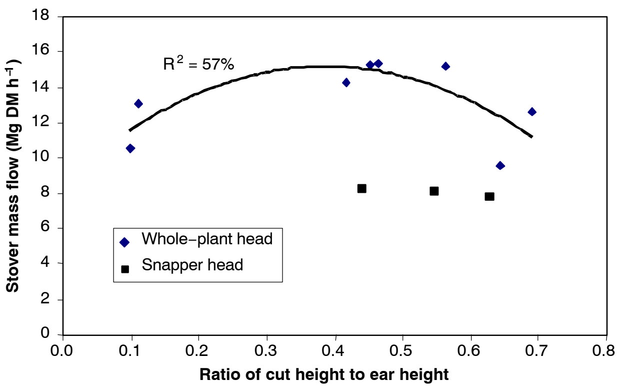

Figure 9. Dry mass flow rate of the stover fraction as a function of head height for the whole-plant corn head and conventional snapper head.

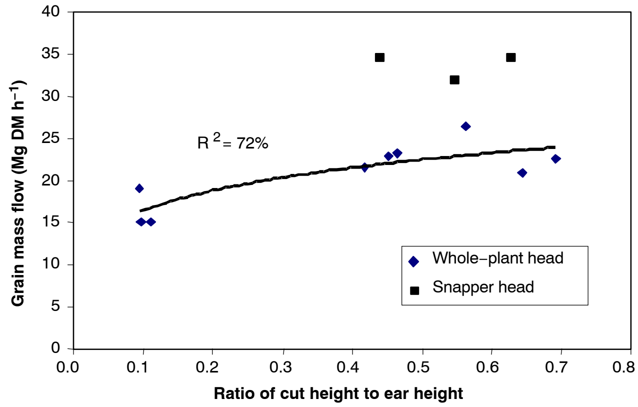

Figure 10. Dry mass flow rate of the grain fraction as a function of head height for the whole-plant corn head and conventional snapper head.

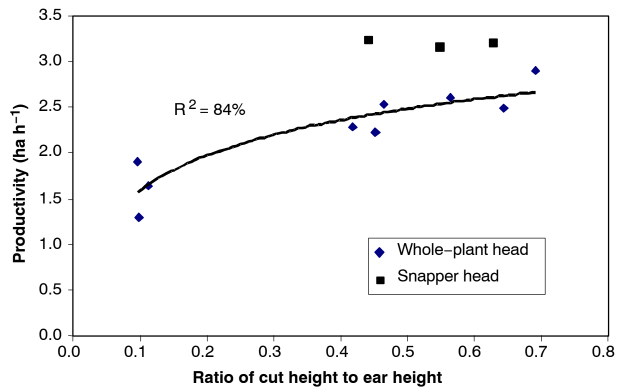

Figure 11. Area productivity of the modified grain combine as a function of head height for the whole-plant corn head and conventional snapper head.

Independent of head type or cut height, ground speed was altered so that engine speed was maintained at approximately 2260 rpm in an attempt to maintain similar harvester loading between treatments. The maximum stover mass flow rate occurred at the intermediate cut height (fig. 9). At the lowest cut height, the stover mass flow rate dropped because processing the tough bottom portion of the stalk caused a reduction in ground speed in greater proportion than the increase in stover DM ingested. At the highest cut height, the amount of stover ingested was low, and ground speed was increased. Here, grain processing started to limit the machine capacity. The average stover dry mass flow rates were 13.5 and 8.1 kg DM h^{-1} for the whole-plant and ear-snapper heads, respectively. Grain mass flow rate and area productivity were almost linearly related to cut height for the modified harvester because higher cut heights ingested less stover and allowed for greater ground speed (figs. 10 and 11). Average grain mass flow rates were 16.4 and 33.7 Mg DM h^{-1} and area productivities were 1.6 and 3.2 ha h^{-1} for the whole-plant (lowest cut height) and ear-snapper heads, respectively, representing a drop in harvesting capacity of 50% when harvesting the whole plant.

Regression equations that describe the harvest performance as a function of cut height were either 1st or 2nd order polynomials or logarithmic functions of cut height (table 4). These equations were generated with a limited data set under one field condition, so they may not adequately describe machine performance in other conditions.

Stover Chemical Composition

Glucan, mannan, and lignin content generally did not vary by position on the stalk, but xylan, galactan, and arabinan content tended to increase from bottom to top of the stalk (table 5). The stalk fraction was higher in glucan but lower in xylan than the cob or husk fractions. The cob fraction had the second lowest glucan content but the highest xylan content. Glucan, galactan, mannan, xylan, and arabinan content have been shown to be good predictors of theoretical ethanol yield (Ruth and Thomas, 2003). The NREL theoretical ethanol yield calculator (U.S. DOE, 2005) and these sugar contents were used to predict estimated ethanol yield. Based on estimated ethanol yield per dry mass of product, the cob, husk, and top half of the stalk would provide greatest ethanol yield efficiency (table 5). However, the dry mass yield of these three fractions only made up about 40% of the total stover yield (table 2), so targeting only these fractions for harvest would result in low ethanol yield per unit area.

The chemical composition of the aggregate stover harvested at the three cut heights was quite similar (table 6). Of the five important polymeric sugars, only glucan and xylan were significantly different for the different cut heights. The lowest height produced the greatest glucan because of greater capture of the bottom stalk fraction (table 3). The highest cut height produced the greatest xylan content because the xylan-rich cob and husk made up a greater portion of the total stover (tables 3 and 6). Lignin content increased with lower cut height as more of the stalk fraction was captured. Compared

Table 4. Coefficients of regression equations for various performance parameters as a function of ratio of cut height to ear height (X) for whole-plant corn head.

Figure	Parameter	Units	$A \cdot X^2$	$B \cdot X$	C	R^2
2	Fraction of total DM	%	–40.5	–25.3	97.7	0.93
3	Fraction of stalk DM	%	––	–80.8	102.3	0.95
3	Fraction of leaf DM	%	–118.1	8.0	90.6	0.83
4	Aggregate stover moisture	% w.b.	––	–25.6	52.9	0.95
5	Fraction of initial moisture	%	–21.4	–62.4	99.1	0.97
6	Aggregate stover density	kg DM m^{-3}	––	10.7[a]	54.7	0.88
7	Aggregate particle-size	mm	––	–18.6[a]	46.8	0.90
8	Aggregate stover density[b]	kg DM m^{-3}	––	–39.4[a]	207.8	0.89
9	Dry mass flow of stover	Mg DM h^{-1}	–42.7	32.6	8.6	0.57
10	Dry mass flow of grain	Mg DM h^{-1}	––	3.9[a]	25.2	0.72
11	Area productivity	ha h^{-1}	––	0.6[a]	2.9	0.84

[a] Natural log of cut height ratio or particle-size.
[b] Aggregate stover density (kg DM m^{-3}) as function of particle-size (mm).

Table 5. Chemical composition using NIRS analysis and NREL Stover9 calibration and estimated ethanol yield of various fractions of corn plant prior to harvest.[a]

	Fraction of Total DM (%)								Estimated Ethanol Yield	
Corn Plant Fraction	Glucan	Xylan	Galactan	Arabinan	Mannan	Lignin	Protein	Structural Inorganics	L Mg^{-1} DM	L ha^{-1}
Bottom stalk	36.0 e	17.0 a	1.0 a	1.5 a	0.4 a	14.5 d	2.9 b	3.8 e	406 a	877 f
Mid-bottom stalk	34.8 d	18.0 b	1.3 b	2.2 b	0.5 ab	14.1 d	3.3 c	1.6 c	412 b	776 e
Mid-top stalk	35.3 d	19.2 d	1.6 c	2.8 c	0.5 ab	14.4 d	3.3 c	1.7 c	432 c	324 b
Top stalk	36.4 e	21.0 e	1.6 c	2.7 c	0.4 a	14.2 d	2.5 a	2.8 d	452 d	52 a
Cob	31.9 b	28.3 g	1.4 b	2.7 c	1.0 c	12.1 c	4.0 d	0.0 a	477 f	892 g
Husk	33.2 c	23.7 f	2.0	3.7 e	0.6 b	11.4 b	2.9 b	1.1 b	459 e	496 c
Leaf	31.2 a	18.8 c	1.8 d	3.4 d	0.6 b	9.7 a	5.8 e	2.0 c	405 a	698 d
LSD (P = 0.05)	0.5	0.3	0.1	0.1	0.1	0.4	0.2	0.4	5	8

[a] Values in the same column followed by different letters are significantly different at the 95% confidence level.

Table 6. Chemical composition using NIRS analysis and NREL Stover9 calibration and estimated ethanol yield of aggregate stover as a function of harvest height for the whole-plant corn head.

	Fraction of Total DM (%)								Estimated Ethanol Yield	
Ratio of Head to Ear Height	Glucan	Xylan	Galactan	Arabinan	Mannan	Lignin	Protein	Structural Inorganics	L Mg^{-1} DM	L ha^{-1}
Measured[a]										
0.10	35.8 c	20.4 a	1.5	2.6	0.5	13.4 c	2.8 a	1.2 a	443 b	3945 c
0.48	34.5 b	20.3 a	1.5	2.6	0.5	12.6 b	2.9 ab	1.7 ab	435 a	3230 b
0.60	33.9 a	21.1 b	1.5	2.7	0.5	12.1 a	3.0 b	1.6 b	431 a	2600 a
LSD (P = 0.05)	0.5	0.4	0.1	0.2	0.0	0.3	0.1	0.3	5	39
Estimated[b]										
0.10	33.7	19.6	1.2	2.6	0.6	12.7	3.7	1.8	420	3742
0.48	33.6	20.1	1.3	2.7	0.6	12.6	3.7	1.7	424	3176
0.60	33.5	21.0	1.3	2.7	0.7	12.5	3.7	1.5	430	2571

[a] Values in the same column followed by different letters are significantly different at the 95% confidence level.
[b] Estimated chemical composition based on fractional mass capture (table 3) and chemical composition of fractions (table 5).

to the lowest height, harvesting at the intermediate height significantly lowered the aggregate stover glucan content, primarily due to the lower capture rate of the glucan-rich bottom section of the stalk. Based on the high glucan content at the lowest harvest height, this treatment produced the highest estimated ethanol yield per unit mass, but specific estimated ethanol yield was only 3% different between the high and low cut heights. However, based on relative differences in stover capture rate, harvesting at the low cut height would increase ethanol yield per unit area by 52% compared to the highest cut height.

Storage

The average density in a bag silo of stover harvested by shredding, windrowing, and chopping with a precision-cut forage harvester was 140 kg DM m^{-3} (Shinners et al., 2007b). In that study, storage losses were 1.4% and 3.8% of total DM when stover moisture was 39.9% and 55.7% (w.b.), respectively. Stover harvested using the single-pass harvester was noticeably more difficult to tightly pack in the silo bag, and final stored densities were 93, 115, and 125 kg DM m^{-3} for the grain, leafy, and low-lignin hybrids, respectively. The relatively low density probably led to higher oxygen level in the material and greater DM loss (table 7). Pockets of mold were observed frequently throughout the bag, especially at the surface where the bag was not held tightly against the stover.

Table 7. Chemical composition, fermentation products, and storage losses for chopped wet stover stored in a plastic bag silo for roughly eight months.[a]

Corn Hybrid Type	Moisture (% w.b.) Initial	Moisture (% w.b.) Final	DM Loss (% of total)	Fraction of Total DM (%) Ash	CP	ADF	NDF	pH	Fermentation Products (% of total DM) Lactic acid	Acetic acid
Grain	42.8	44.3	6.0	5.1 b	4.0	48.5 c	79.4 b	4.8 b	2.4 ab	1.2 ab
Leafy	45.6	48.2	6.0	3.5 a	4.2	43.9 b	72.8 a	4.2 a	1.6 a	0.8 a
Low lignin	39.7	41.2	6.2	3.9 a	4.3	39.9 a	71.7 a	4.2 a	3.2 b	1.5 b
LSD (P = 0.05)				0.5	0.5	3.1	3.4	0.3	0.8	0.4

[a] Values in the same column followed by different letters are significantly different at the 95% confidence level.

Ash content of the stover harvested with the single-pass harvester ranged from 3.5% to 3.9% of total DM. Binversie (2005) reported ash contents of 7.9% for windrowed and chopped stover, so the single-pass system shows promise to reduce soil contamination. The significantly higher ADF and NDF contents of the grain variety reflect breeding, which targeted high grain yield and a strong stalk to support the heavy cob. Levels of fermentation products were similar to those reported for windrowed and chopped stover (Shinners et al., 2007b). The low-lignin variety produced the numerically lowest ADF, NDF, and pH and the highest CP, lactic acid, and acetic acid, but DM losses were no different than with the other two varieties.

Conclusions

When using a whole-plant corn head on a grain combine, capture of potential stover DM varied from 48% to 89% for leaves, from 49% to 92% for stalks, and was greater than 90% for husks and cobs, depending on corn head height. With a conventional ear-snapper head, stover capture was 24%, 14%, 97%, and 53% of DM for the leaf, stalk, cob, and husk fractions, respectively.

Stover aggregate moisture was 50.2%, 43.1%, and 36.4% (w.b.) when the corn head height was 10%, 44%, and 63% of ear height, respectively. Aggregate stover moisture was 25.4% (w.b.) with the ear-snapper head.

Single-pass stover had an average particle size of 69 mm and bulk density of 51 and 111 kg DM m^{-3} in the wagon and bag silo, respectively. Aggregate stover particle size increased and density decreased as more of the stalk was harvested.

A greater stover feed rate limited ground speed due to power availability, so area capacity was 1.6, 2.4, and 2.6 ha h^{-1} when corn head height was 10%, 44%, and 63% of ear height, respectively. Whole-plant harvesting reduced area capacity by 50% compared to harvesting with a conventional ear-snapper head (3.2 ha h^{-1}).

Glucan content increased and xylan content decreased as more of the stalk and leaf fractions were captured. Therefore, corn head height did not significantly affect specific ethanol yield per unit mass (average 436 L Mg^{-1} DM). Based on polymeric sugar content, estimated ethanol yield was 3945, 3230, and 2600 L ha^{-1} when the corn head height was 10%, 44%, and 63% of ear height, respectively.

When average moisture of aggregate stover was 42.7%, fermentation of single-pass stover in a bag silo was adequate, with average losses of 6% of total DM.

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References

Albert, W. W., and L. E. Stephens. 1969. Stalklage silage harvested with a converted combine. ASAE Paper No. 69313. St. Joseph, Mich.: ASAE.

ASAE Standards. 2007. S424.1: Method of determining and expressing particle size of chopped forage materials by screening. St. Joseph, Mich.: ASAE.

Ayres, G. E., and W. F. Buchele. 1971. Harvesting and storing corn plant forage. ASAE Paper No. 71665. St. Joseph, Mich.: ASAE.

Ayres, G. E., and W. F. Buchele. 1976. An evaluation of machinery systems for harvesting corn plant forage. ASAE Paper No. 761015. St. Joseph, Mich.: ASAE.

Buchele, W. F. 1976. Research in developing more efficient harvesting machinery and utilization of crop residues. *Trans. ASAE* 19(5): 809-811.

Binversie, B. N. 2005. Collection, harvest, and storage of corn stover as a biomass feedstock. Unpublished MS thesis. Madison, Wisc.: University of Wisconsin, Department of Biological Systems Engineering.

Hames, B. R., S. R. Thomas, A. D. Sluiter, C. J. Roth, and D. W. Templeton. 2003. Rapid biomass analysis: New tools for compositional analysis of corn stover feedstocks and process intermediates from ethanol production. In *Applied Biochem. and Biotech.: Proc. 24th Symposium on Biotechnology for Fuels and Chemicals* 105-108: 5-16.

Hitzhusen, T. E., S. J. Marley, and W. F. Buchele. 1970. Beefmaker II: Developing a total corn harvester. *Agric. Eng.* 51(Nov.): 632-634.

Kim, S., and B. E. Dale. 2003. Global potential bioethanol production from wasted crops and crop residues. *Biomass and Bioenergy* 26(4): 361-375.

Ruth, M. L., and S. R. Thomas. 2003. The effect of corn stover composition on ethanol process economics. Presented at the 25th Symposium on Biotechnology for Fuels and Chemicals. Golden, Colo.: National Renewable Energy Laboratory. Available at: www.eere.energy.gov/biomass/pdfs/34040.pdf. Accessed 16 September 2006.

Schroeder, K. R., and W. F. Buchele. 1969. A total corn harvester. ASAE Paper No. 69314. St. Joseph, Mich.: ASAE.

Shinners, K. J. 2003. Engineering of silage harvesting equipment: From cutting to storage structure. In *Silage Science and Technology, Agronomy*, 361-404. Monograph No. 42. Madison, Wisc.: American Society of Agronomy.

Shinners, K. J., B. N. Binversie, and P. Savoie. 2003. Whole-plant corn harvesting for biomass: Comparison of single-pass and multi-pass harvest systems. ASAE Paper No. 036089. St. Joseph, Mich.: ASAE.

Shinners, K. J., and B. N. Binversie. 2007a. Fractional yield and moisture of corn stover biomass produced in the northern U.S. corn belt. *Biomass and Bioenergy* (in press).

Shinners, K. J., B. N. Binversie, R. E. Muck, and P. J. Weimer. 2007b. Comparison of wet and dry corn stover harvest and storage. *Biomass and Bioenergy* 31(4): 211-221.

U.S. DOE. 2005. Theoretical ethanol yield calculator. Washington, D.C.: U.S. Department of Energy. Available at: www.eere.energy.gov/biomass/ethanol_yield_calculatorhtml. Accessed 16 September 2006.

Van der Werf, H. M. G., and A. J. Muller. 1994. Estimation of yield of silage maize dry matter from volume harvested or by sampling harvested trailer loads. *J. Agric. Eng. Res.* 57(3): 207-212.

Wiersma, D. W., and B. J. Holmes. 2004. Estimating the weight of forage in a forage wagon. *Focus on Forage* 3(4): 1-2. Madison, Wisc.: University of Wisconsin Extension. Available at: www.uwex.edu/ces/crops/uwforage/ForageBox.pdf. Accessed 16 September 2006.