The Society for engineering in agricultural, food, and biological systems

An ASAE Meeting Presentation
Paper Number: 056051

Characteristic Performance and Yields using a Single-Pass, Split-Stream Maize Grain and Stover Harvester

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Written for presentation at the
2004 ASAE/CSAE Annual International Written for presentation at the
2005 ASAE Annual International Meeting
Sponsored by ASAE
Tampa Convention Center
Tampa, Florida
17 - 20 July 2005

Abstract. A grain combine was 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, 49 to 92% for stalks, and greater than 90% for husks and cobs, depending upon corn head height. 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. Greater MOG feedrate limited ground speed due to power availability, so area capacity was 2.3, 2.8 and 3.4 ha/h when corn head height was 10, 44 and 63% of ear height, respectively. Whole-plant harvesting reduced area capacity by nearly 61% compared to harvesting with a conventional snapping-roll head. Single-pass stover had an average particle size of 69 mm and bulk density of 51 and 110 kg DM/m^3 in the wagon and bag silo, respectively. Based on polymeric sugar content, estimated ethanol yield was 3,945, 3,230, and 2,600 L/ha when the corn head height was 10, 44 and 63% of ear height, respectively. 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 stover, density, particle-size

Introduction

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 obstacle 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., 2005b). Problems with this system include poor drying conditions in the Upper Midwest due to 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 available stover mass), and high cost.

Harvesting and storing wet corn stover virtually eliminates the need for field drying, which allows 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., 2005b). 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 with two crop streams. An alternative single-pass system is to adopt a whole-plant corn head from a forage harvester to the grain combine harvester 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/dry Mg harvested, stored and delivered to the processing facility (Shinners and Binversie, 2003). 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.

Objectives

The objectives of this research were to modify a grain combine to harvest the whole-plant in a single-pass while creating two separate crop streams, grain and stover; to quantify the performance of the modified harvester; to quantify the storage characteristics of the ensiled stover; and to estimate the chemical composition and ethanol yield of the harvested stover fractions using NIRS techniques.

Materials and Methods

Machine Description

Two modifications were made to a John Deere[1] model 9760 combine so that single-pass, split-stream harvesting could be investigated (fig. 1). First, a John Deere[1] model 666R whole-plant corn head normally intended for use with a forage harvester was adapted to the combine harvester to simultaneously capture the stover and grain fractions. Modifications to the gathering auger were required to produce satisfactory feeding to the combine feeder house. Additionally, 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 2,500 rpm, was 1,310 mm wide, with 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. The 450 mm diameter blower was 510 mm wide, had 12 paddles and was belt driven at 1,800 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 wagon was equipped with load cells to determine the weight of the contents. A remote camera was used by the operator to monitor the spout position and wagon fill. 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.

Quantifying Machine Performance

A replicated block field experiment was conducted to quantify the performance of the modified harvester. Tests were conducted on November 3rd through 5th, 2005 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 was limited by the lowest height 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 separate plots of 150 m length by 4.6 m wide. Three replicate tests were conducted per treatment and the four treatments and replicates were randomly assigned to the 12 plots.

[1] Mention of trade names in this manuscript are made solely to provide specific information and do not imply endorsement of the product or service by the University of Wisconsin-Madison and the USDA–ARS

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

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

Variety	Pioneer[1] 35R58
GRM	105 day
Planting date	4/29/05
Harvest dates	11/3 – 11/5/05
Ear height .. mm	1,213
Standing height .. mm	2,683
Plant population .. plants / ha	73,688
Pre-harvest loss .. Mg DM / ha	
Leaf	0.44
Stalk	0.12

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 103º C for 24 h, and then the dry mass 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 – 5th nodes), mid-bottom (5th – 9th nodes), mid-top (9th – 13th nodes) and top (> 13th nodes) fractions (Shinners et al., 2005a). For two of the grids, all eight fractions were weighed and the fractions oven dried as described above. The fractions from the third grid were intended for chemical composition analysis (see below), and were dried at 65º C for 72 h.

After pre-harvest data collection, the harvester was used to harvest the plot. Ground speed was altered with the harvester hydrostatic transmission so that engine speed was maintained at approximately 2,260 rpm in an attempt to maintain similar harvester loading between treatments. Threshing cylinder speed was maintained at about 300 rev/min and cleaning fan speed at 920 rpm. Time to harvest the plot was recorded so that ground speed, and stover and grain mass-flow-rate could be calculated. Actual cut height as determined by 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. Several random grab samples were collected from each load. Three samples were used to determine stover moisture by oven drying for 24h at 103º C. Three additional samples were collected to determine chemical composition (see below), so they were dried at 65º C for 72 h. An additional two samples were collected for particle-size analysis using procedures described in ASAE Standard S424.1 (ASAE, 2005). The harvester grain tank was unloaded and the grain weight was determined to the nearest 2 kg by driving the cart over a drive over truck scale. Several random grab samples were collected to determine grain moisture by drying at 103º C for 24 h.

Differences between treatments were analyzed using analysis of variance and statistical differences were determined using a least-significant-difference test (LSD) 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 performed. The regression analysis was carried out using only the data collected while using the whole-plant corn head, not the conventional snapper head. The R^2 values reported in the plots reflects only the data collected with the whole-plant head.

Stover Chemical Composition

The chemical composition of the stover fractions (cob, husk, leaf, and stalk by section) plus the aggregate harvested stover was determined analytically using near-infrared spectroscopy (NIRS). The collected spectra were used to estimate chemical composition using the "Stover9" calibration developed by Hames et al.(2003) at the National Renewable Energy Laboratory (NREL) in Golden, CO. After oven drying (see above), samples for analysis were ground in a conventional laboratory hammer mill equipped with a 2 mm screen. Samples were stored in sealed plastic bags until scanning. The samples were scanned using a Foss NIR Systems model 6500 Forage Analyzer with a sample transport module and a standard reflectance detector array. The spectral analyzer used two silicon detectors to monitor visible light from 400-850 nm and four lead-sulfide detectors to monitor NIR light from 850-2500 nm. Each sample was split into three replicate sub-samples and packed in conventional 60 mL sample cells supplied by Foss. For each cell, 32 spectra were collected and averaged and a reference scan was conducted before and after each cell. Standard check cells were scanned three times at the beginning and end of the analysis to check for instrument drift and for comparison with NREL instruments. 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 November 11th and 12th, 2005 with the modified harvester and the stover fraction ensiled. Three corn varieties were used: a typical grain hybrid (Pioneer[1] 35R58), a silage leafy hybrid (Northup King[1] N48-V8) and a silage low lignin variety (Mycogen[1] 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 collected in a forage wagon equipped with load cells to determine the harvested mass to the nearest 2 kg. 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. Prior to placing in storage, sub-samples were collected for moisture and particle-size determination. Moisture was determined on three sub-samples per load by oven drying at 103ºC for 24 h. Particle-size was determined on three sub-samples per silo.

The silo bags were opened on 6/22/05 after about eight months in storage. The stover was removed with a loader and spillage was hand-collected to minimize take-out losses. The removed stover was weighed on a truck scale accurate to the nearest 2 kg. Three sub-samples were taken at each load location and oven dried at 65ºC for 72 h for moisture determination to insure that volatiles formed from fermentation during the ensiling process were not driven off. An additional sample was collected from each load location and oven dried at 65ºC, hammer-milled to 1 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.

Results

Machine Operation

Crop characteristics just prior to harvest were considered typical for this variety and location (Shinners et al., 2005a). At the time of harvest, the stalk made up over 50% of the total DM of the stover fraction and contained greater 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 greater than 50% of the stover water. The cob, husk and top half of the stalk made up about 40% of the stover DM, but less than 11% of the available water in the stover. Successful preservation by fermentation will require adequate aggregate stover moisture which can only be accomplished by harvesting a portion of the bottom half of the stalk.

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 allowed harvest of greater than 90% of the cob and husk regardless of cut height (table 3). The snapper head also was able to harvest 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). By the time that harvest occurred, the vast majority of the leaves had drooped, so at the two highest cut heights, leaves were cut by the stalk cutoff disks and were lost. The 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 height ratios (table 3). The grain filled cobs had drooped by the time harvest occurred, so cut height of the whole-plant head was limited to 63% of ear height to reduce grain loss. Nonetheless, there was an occasional ear that was sheared at that cut height, so grain loss was very high for that ratio (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 ratio of cut 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 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 corn head was set to capture the bottom section of the stalk (table 3). The whole-plant corn head was able to capture from 50 to 90% of the available stover moisture, depending upon cut height (fig. 5). The storage scheme envisioned for direct harvested stover involves preservation by ensiling, and moisture is needed for adequate preservation. Chopped stover ensiled in a bag silo was well preserved for 12 months at moistures as low as 42% (Shinners et al., 2005b), so it appears that the two lowest cut heights would provide adequate stover moisture. It is unknown how well stover harvested with the snapper head would preserve given the low moisture of the aggregate.

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

	Yield .. Mg / ha		Fraction of stover .. %		Moisture
	DM	**Water**	**DM**	**Water**	**% w.b.**
Bottom stalk	2.16	5.32	22.6	56.9	71.1
Mid-bottom "	1.88	1.65	19.6	17.6	46.8
Mid-top "	0.75	0.22	7.9	2.4	22.7
Top "	0.13	0.05	1.4	0.6	28.4
Total "	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

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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.

Head type	Ratio of head to ear height	Fraction of standing stover DM harvested					Aggregate stover moisture % w.b.	Fraction of grain DM		
		Cob	Husk	Leaf	Stalk	Stover		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
"	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
"	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

* – Averages with different subscripts in the same column are significantly different at 90% confidence.

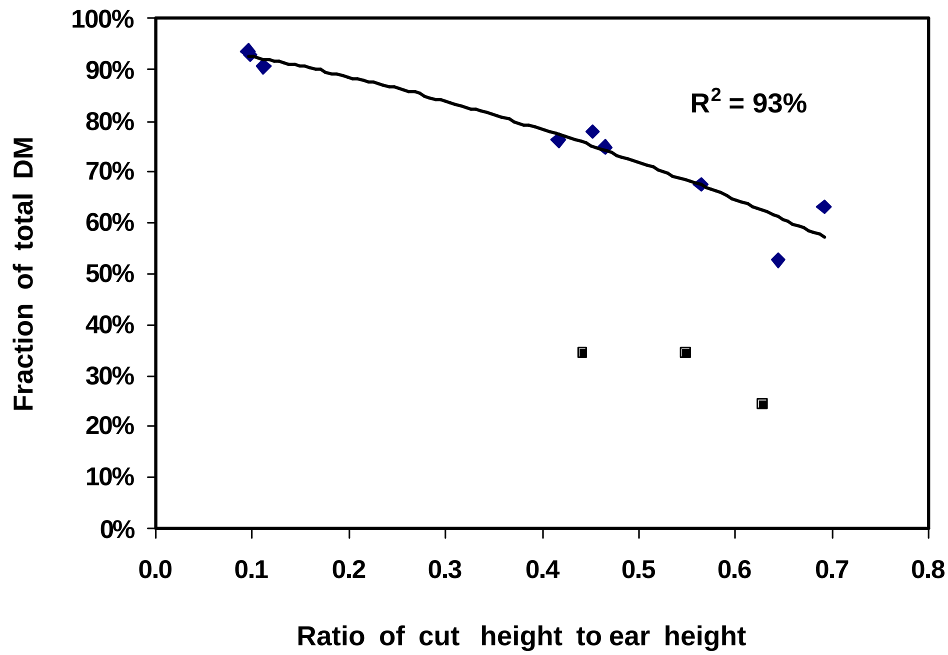


Figure 2. Fraction of total stover DM harvested as a function of cut height for the whole-plant corn head (?) and conventional snapper head (■).

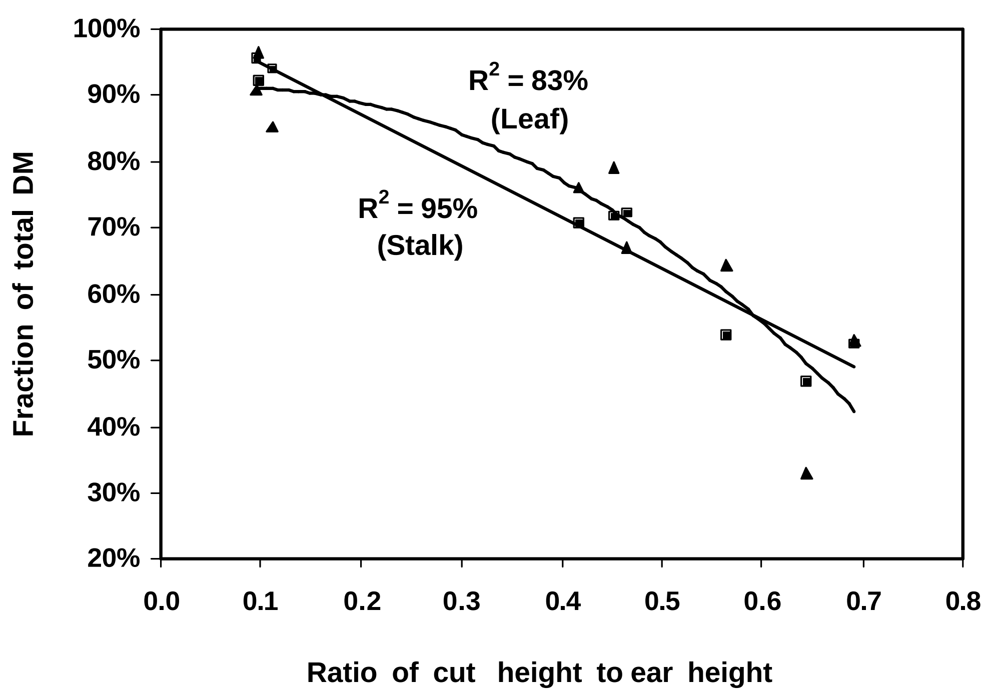


Figure 3. Fraction of total stalk (■) or leaf (?) DM harvested as a function of cut height for the whole-plant head only.

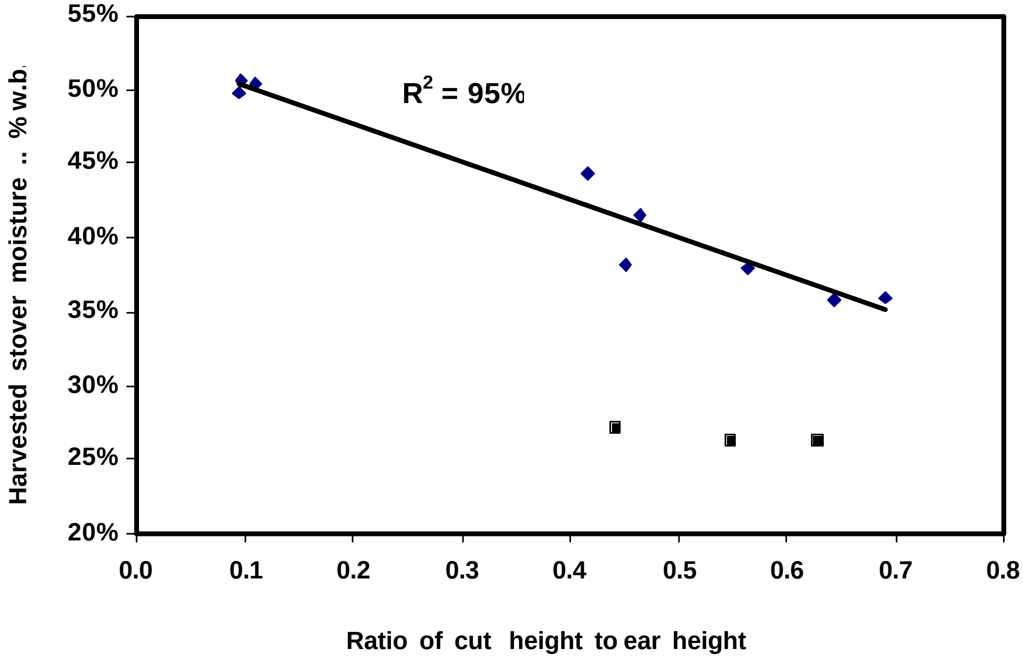


Figure 4. Moisture content of the aggregate stover harvested as a function of cut height for the whole-plant corn head (?) and conventional snapper head (■).

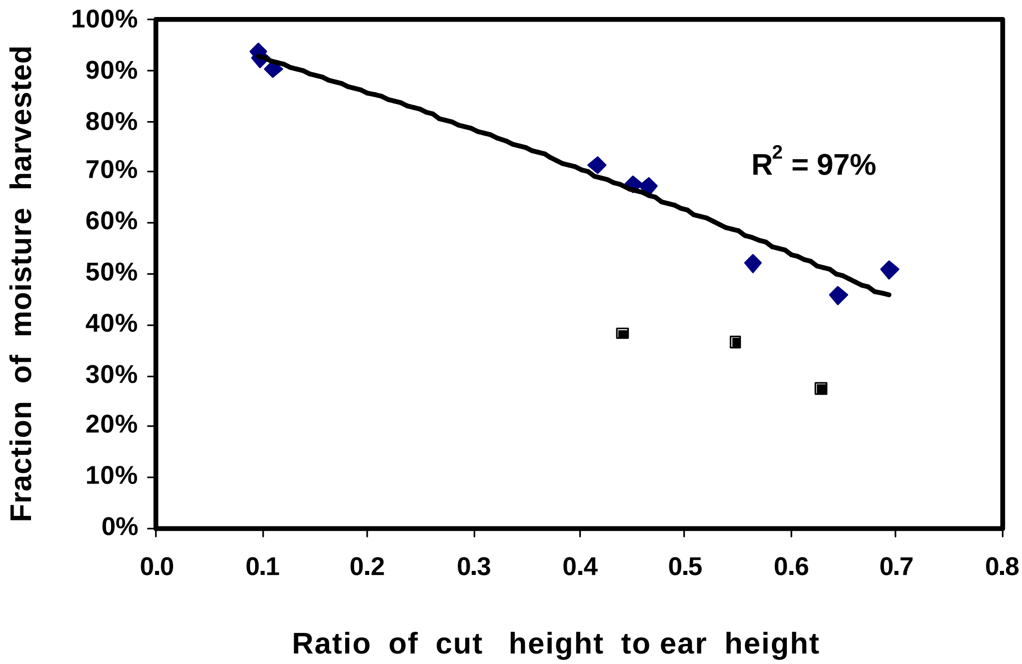


Figure 5. Fraction of water available in total stover as a function of cut height for the whole-plant corn head (?) and conventional snapper head (■).

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 finally 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., 2005b). Chopped stover density was lower than whole-plant density because stover lacked the high density grain fraction and because it's ALC was quite long. In this study, the stover density in the wagon was no greater 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 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 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. Also, the stover could not be well oriented for cutting in the flail chopper. Shipping volume and weight restrictions constrain 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 do a better job of aligning and metering the stover into a cutting mechanism will be required to achieve the desired density.

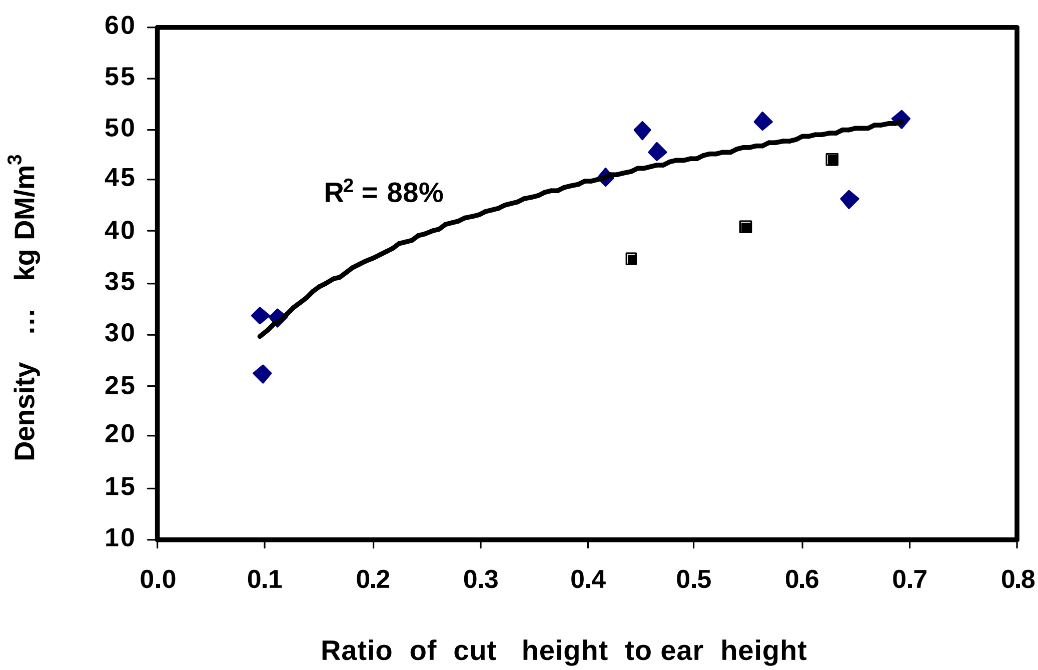


Figure 6. Dry bulk density of aggregate harvested stover as a function of cut height for the whole-plant corn head (?) and conventional snapper head (■).

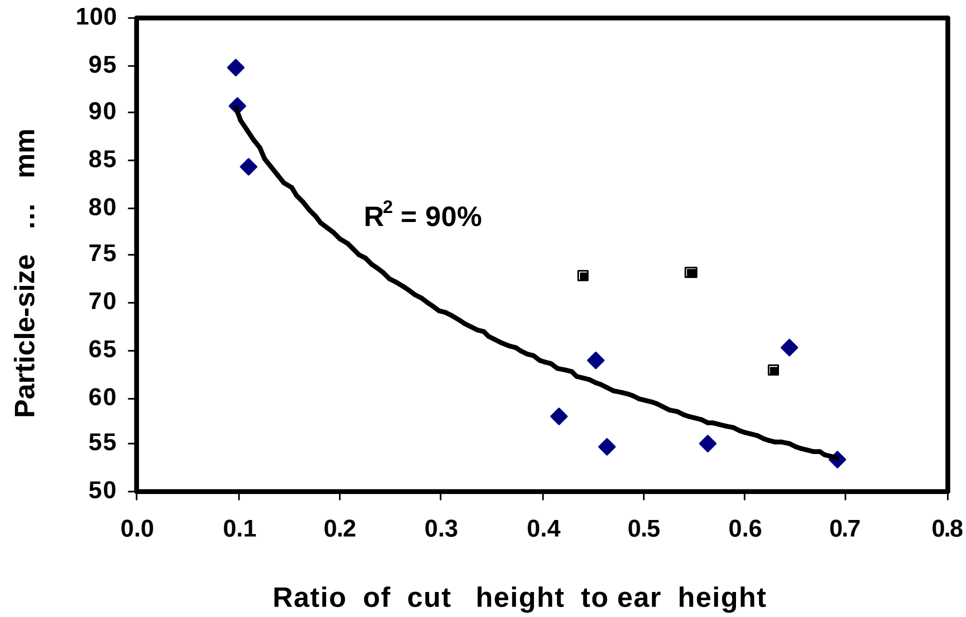


Figure 7. Aggregate stover particle-size as a function of cut height for the whole-plant corn head (?) and conventional snapper head (■).

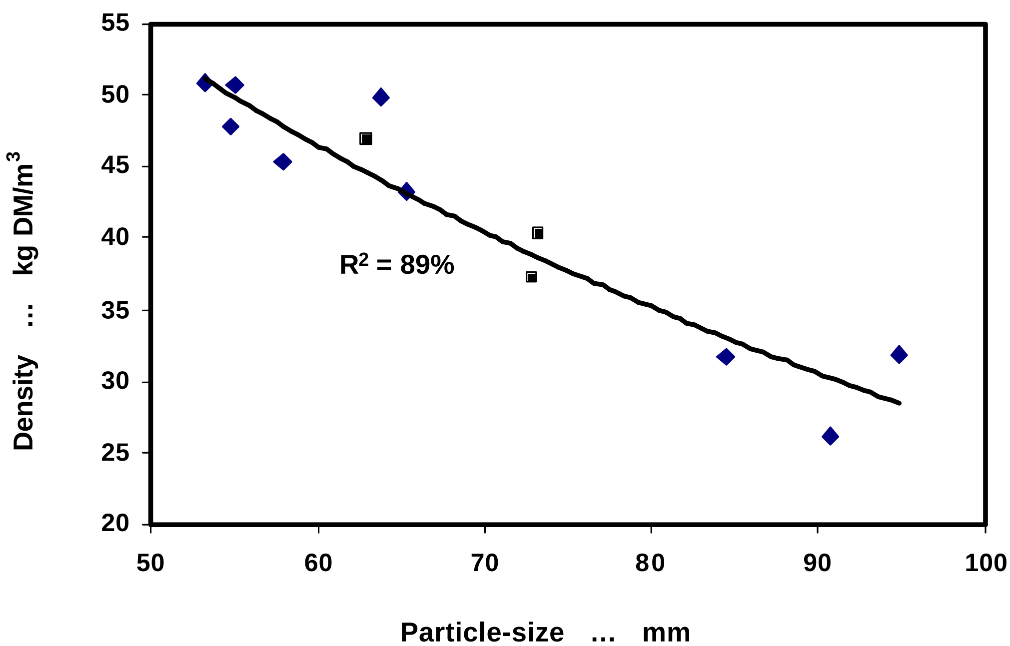
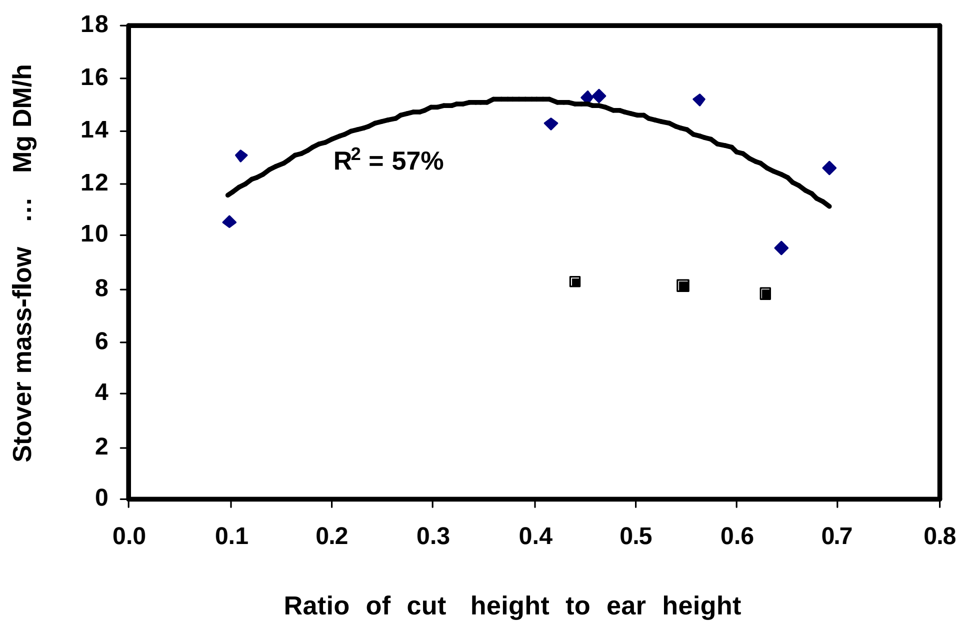


Figure 8. Dry bulk density of the aggregate stover as a function of particle-size for the whole-plant corn head (?) and conventional snapper head (■).

Independent of head type or cut height, ground speed was altered so that engine speed was maintained at approximately 2,260 rev/min 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, 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, but the stover capture rate was only 67% so mass flow-rate was reduced. The average stover dry mass flow-rate was 13.5 and 8.1 kg DM/h for the whole-plant and 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-rate was 16.4 and 33.7 Mg DM/h and area productivity 1.6 and 3.2 ha/h for the whole-plant head at the lowest cut height and the snapper head, respectively, representing a drop in harvesting capacity of 50%.



<u>Figure 9.</u> Dry mass flow-rate of the stover fraction as a function of head height for the whole-plant corn head (?) and conventional snapper head (■).

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.

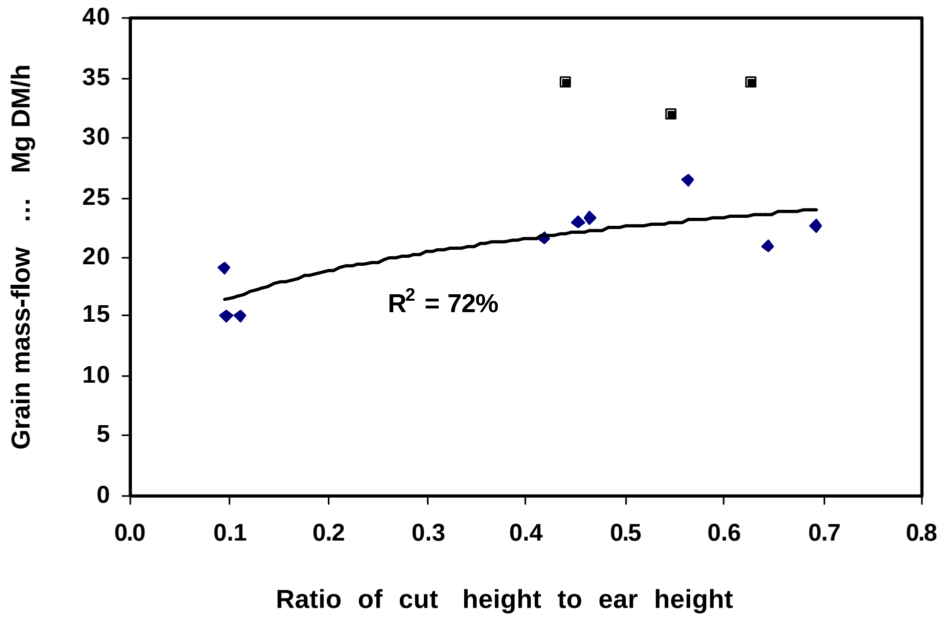


Figure 10. Dry mass flow-rate of the grain fraction as a function of head height for the whole-plant corn head (?) and conventional snapper head (■).

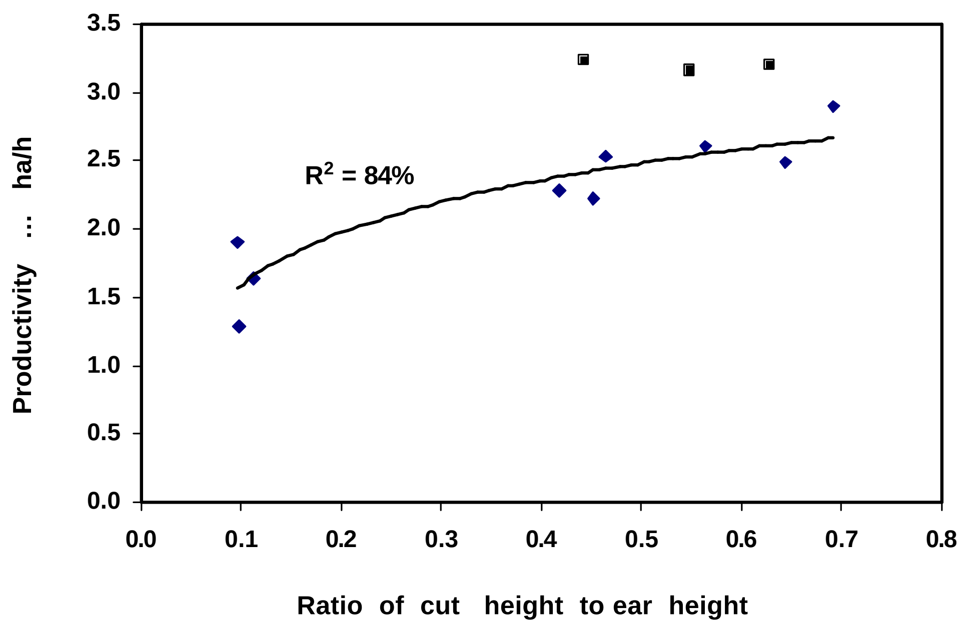


Figure 11. Area productivity of the modified grain combine as a function of head height for the whole-plant corn head (?) and conventional snapper head (■).

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 No.	Parameter	Units	$A \bullet X^2$	$B \bullet X$	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
"	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/m^3		10.7#	54.7	0.88
7	Aggregate particle-size	mm		-18.6#	46.8	0.90
8	Aggregate stover density@	kg/m^3		-39.4#	207.8	0.89
9	Dry mass flow of stover	Mg/h	-42.7	32.6	8.6	0.53
10	Dry mass flow of grain	Mg/h		3.86#	25.2	0.72
11	Area productivity	ha/h		0.6#	2.9	0.84

- Natural log of cut height ratio or particle-size

@ - Aggregate stover density (kg/m^3) as function of particle-size (mm).

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 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. Polymeric sugar content such as glucan, galactan, mannan, xylan and arabinan have been shown to be good predictors of theoretical ethanol yield (Ruth and Thomas, 2003). The NREL theoretical ethanol yield calculator (Anon., 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 3), 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 (table 3 and 6). Lignin content increased with lower cut height as more of the stalk fraction was captured. Compared 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 2.3% different between the high and low cut height. However, based on relative differences in stover capture rate, harvesting at the low cut height would increase ethanol yield per unit area by 44% compared to the lowest cut height.

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

Corn plant fraction	Glucan	Xylan	Galactan	Arabinan	Mannan	Lignin	Protein	Structural Inorganics	Estimated Ethanol Yield	
	Fraction of total DM .. %								L / kg DM	L / ha
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 "	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 "	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 "	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

* – Averages with different subscripts in the same column are significantly different at 95% confidence.

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.

Ratio of head to ear height	Glucan	Xylan	Galactan	Arabinan	Mannan	Lignin	Protein	Structural Inorganics	Estimated Ethanol Yield	
	Fraction of total DM .. %								L / kg DM	L / ha
Measured										
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	$3,945_c$
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	$3,230_b$
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	$2,600_a$
LSD* (P = 0.05)	0.5	0.4	0.1	0.2	0.0	0.3	0.1	0.3	5	39
Estimated#										
0.10	33.7	19.6	1.2	2.6	0.6	12.7	3.7	1.8	420	3,742
0.48	33.6	20.1	1.3	2.7	0.6	12.6	3.7	1.7	424	3,176
0.60	33.5	21.0	1.3	2.7	0.7	12.5	3.7	1.5	430	2,571

– Estimated chemical composition based on fractional mass capture (table 3) and chemical composition of fractions (table 5).
* – Averages with different subscripts in the same column are significantly different at 95% confidence.

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., 2005b). In that study, storage losses were of 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 pack tightly in the silo bag and final stored density was 93, 115 and 125 kg DM/m^3 for the grain, leafy and low lignin hybrids, respectively. This 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. Levels of fermentation products were similar to those reported for windrowed and chopped stover (Shinners et al., 2005b). The low lignin variety produced the numerically lowest pH and the highest lactic and acetic acids, but DM losses were no different than with the other two varieties.

Table 7. Final storage data for chopped wet stover stored in a plastic bag silo for roughly eight months.

Corn hybrid type	Initial moisture % w.b.	Final moisture % w.b.	DM loss % of total	Ash % of total DM	pH	Fermentation products … % of DM	
						Lactic acid	Acetic acid
Grain	42.8	44.3	6.0	5.1_b	4.8_b	2.4_{ab}	1.2_{ab}
Leafy	45.6	48.2	6.0	3.5_a	4.2_a	1.6_a	0.8_a
Low lignin	39.7	41.2	6.2	3.9_a	4.2_a	3.2_b	1.5_b
LSD* (P = 0.05)				0.5	0.3	0.8	0.4

* – Averages with different subscripts in the same column are significantly different at 95% confidence.

Conclusions

- When using a whole-plant corn head on a grain combine, capture of potential stover DM varied from 48 to 89% for leaves, 49 to 92% for stalks, and greater than 90% for husks and cobs, depending upon corn head height. With a conventional 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 moisture was 25.4% (w.b.) with the snapper roll head.

- Single-pass stover had an average particle size of 69 mm and bulk density of 51 and 110 kg DM/m^3 in the wagon and bag silo, respectively. Aggregate stover particle-size increased and density decreased and as more of the stalk was harvested.

- Greater MOG feedrate limited ground speed due to power availability, so area capacity was 2.3, 2.8 and 3.4 ha/h when corn head height was 10, 44 and 63% of ear height, respectively. Whole-plant harvesting reduced area capacity by nearly 61% compared to harvesting with a conventional snapping-roll head.

- Glucan content increased and xylan content decreased as more of the stalk and leaf fractions were captured. Therefore, there was little difference in the estimated ethanol yield per stover unit mass (average 436 L/kg DM). Based on polymeric sugar content, estimated ethanol yield was 3,945, 3,230, and 2,600 L/ha when the corn head height was 10, 44 and 63% of ear height, respectively, due to differences in stover capture rate.

- 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.

Acknowledgements

This research was partially sponsored by the University of Wisconsin College of Agriculture and Life Sciences, John Deere Harvester Works, John Deere Technical Center, John Deere Ottumwa Works, US Dairy Forage Research Center (USDA-ARS) and the Department of Energy. This research could not have been completed without the assistance of the staff of the Arlington Agricultural Research Station. Special thanks to Bonnie Hames, Senior Chemist at the National Renewable Energy Laboratory in Golden, CO for her assistance with the chemical composition analysis.

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