2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Meeting Presentation
Paper Number: 095652

SINGLE- AND TWO-PASS CORN STOVER HARVESTING SYSTEMS

Kevin J. Shinners – Professor of Agricultural Engineering
Robert G. Bennett – Graduate Research Assistant
Daniel S. Hoffman – Former Graduate Research Assistant
Department of Biological Systems Engineering
University of Wisconsin

Written for presentation at the
2009 ASABE Annual International Meeting
Sponsored by ASABE
Grand Sierra Resort and Casino
Reno, Nevada
June 21 – June 24, 2009

Abstract. *To improve the performance of a single-pass combine used to harvest corn grain and stover, the flail chopper used to process the stover on previous harvester iterations was replaced with forage harvester feedroll and cutterhead components. These precision-cut components improved material flow and combine performance. The change from the flail chopper to the precision-cut stover processor increased area productivity from 1.4 to 2.2 ha/h, decreased specific fuel consumption from 33.4 to 20.9 L/ha and decreased grain lost to the stover from 8.2 to 3.9%. Despite the improvements in combine performance, the single-pass stover system was 39% less productive than the conventional grain harvest system and was challenged by difficulties with handling and transporting grain and stover at the same time. To overcome these problems, an alternative approach was considered where windrows of stover were formed at the time of grain harvest, followed by stover harvest in a second-pass. Modifications were made to a corn head to gather the stalks and leaves and formed them into a windrow. The cob and husk were then placed on top of the windrow as this material was ejected from the rear of the combine. Because the cob was placed on top of the windrow at formation, 94% of the available cob was harvested with this two-pass system, compared to 48% for the conventional system which used shredding and raking stover after grain harvest. Because the two-pass system did not involve forming windrows by displacing stover across the ground, the ash content was 40% less than with conventional stover harvest practices. The area productivity at grain harvest of the two-pass system was 9% less than the conventional harvest system. Total specific fuel use to harvest grain and stover for the single- and two-pass systems was 1.38 and 1.81 L/Mg DM harvested, respectively. This difference may be reduced in the future if larger windrows are formed by merging to better match the capacity of the forage harvester. The particle-size of the stover harvested in a second pass with a forage harvester was 54% smaller than single-pass stover because a shorter length-of-cut could be used. The two-pass system required two fewer operations compared to conventional stover harvest practices. The formation of windrows at grain harvest allows for manipulation of moisture by field curing and may make packaging in dry bales possible compared to the single-pass system.*

Keywords. *Biomass; chemical composition; corn stover; density; feedstock; losses; particle-size; storage.*

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 or the USDA-ARS.

SINGLE- AND TWO-PASS CORN STOVER HARVESTING

INTRODUCTION

Corn stover consists of all the above ground, non-grain fractions of the plant including the stalk, leaf, cob and husk. Corn stover has great potential as a biomass feedstock in North America, with potential annual yields of 130 Tg producing 38.4 GL of ethanol (Kim and Dale, 2003). The widespread utilization of corn stover as a biomass feedstock is challenged by costs associated with its harvest, transport and storage.

Corn stover is typically harvested as a dry product and packaged in large round or large square bales, typically involving as many as seven steps after grain harvesting (Shinners et al., 2007b). Problems with this system include slow field drying, short harvesting window, frequent weather delays, soil contamination, and low yield. The fraction of available stover harvested by conventional means ranged from 37 and 50% (Shinners et al., 2007b). The many field operations resulted in the highest costs per unit mass of the systems considered (Shinners et al., 2003).

Harvesting wet stover immediately after grain harvest by combining shredding and windrow formation in one machine and then chopping the formed windrows with a forage harvester can eliminate the need for field drying and raking; and eliminate bale gathering, staging and loading. The fraction of available stover harvested with this system was 55% (Shinners et al., 2007b).

A single-pass harvesting system which combines the harvest of corn grain and stover would further eliminate field operations and reduce costs. Previous research investigated single-pass-harvesting in which the grain and non-grain fractions were separated, processed and transported from the machine in separate streams (Albert and Stephens, 1969; Ayres and Buchele, 1971; Ayres and Buchele, 1976; Burgin, 1941; Buchele, 1976; Hitzhusen et al., 1970; Schroeder and Buchele, 1969). Shinners et al. (2003) estimated single-pass harvesting reduced total harvesting costs of grain and stover by 26% compared to conventional grain and stover harvesting systems.

A single-pass harvester has recently been used to harvest various stover fractions for biomass feedstocks (Shinners et al., 2007c; 2009a). The modified combine harvester collected cob and husk when configured with an ear-snapper head or the stalk, leaf, cob and husk when configured with a whole-plant head from a forage harvester. The non-grain fractions were size-reduced and collected from the rear of the harvester. In addition to the elimination of all but one harvest operation, the attributes of this system included high stover yield, especially of the valuable cob, and low ash content. However, the research identified some shortcomings of the single-pass system. These included reduction in grain harvesting rate and high power consumption, insufficient stover size-reduction, and low stover bulk density. The single-pass system also offers no opportunity to manipulate the stover moisture by field curing. Because stover moisture is often above 25% (w.b.) moisture, stover harvested in a single-pass must be stored anaerobically and preserved by fermentation. Finally, efficient field logistics are challenged by the need to simultaneously handle and transport stover and grain.

An alternative stover harvest system has been proposed that maintains many of the attributes of the single-pass system while overcoming many of its deficiencies. This two-pass system involves modifications to the combine to create a windrow of stover at the time of grain harvest (Kass, 1980; Shinners et al., 2003). After grain harvest, the stover windrow can be harvested in a second pass using a forage harvester or baler. This harvesting system decouples grain and stover harvest, eliminating most of the logistic problems of simultaneous harvest. The system also requires fewer modifications to the combine harvester, and may not appreciably slow the rate of grain harvest. Finally, it allows for the manipulation of stover moisture so that either wet, ensiled storage or harvest and storage in dry bales is possible.

The objectives of this research were to make modifications to an existing single-pass combine harvester (Shinners et al., 2007c; 2009a) to improve productivity, reduce power consumption for stover processing, and reduce stover particle-size. Additional objectives were to modify a corn head to allow formation of a windrow of stover at the time of grain harvest and then to quantify and compare the performance of various single-pass and two-pass harvester configurations.

MATERIALS AND METHODS

DESCRIPTION OF HARVESTER BASE UNIT

Modifications were made to a John Deere model 9750 STS combine so that single- or two-pass stover harvesting could be investigated. Previous iterations of the modified harvester base unit involved the use of a flail chopper to size-reduce the stover fractions exiting the combine (Shinners et al., 2007c; 2009a). When configured with the flail chopper, the single-pass harvester experienced a number of undesirable performance issues, most notably stover tended to re-circulate within the flail chopper leading to plugging and non-uniform particle-size distribution. Material re-circulation also negatively affected capacity because ground speed had to be limited to prevent plugging. To overcome these performance deficiencies, the flail chopper was replaced with the feedrolls, cutterhead and flywheel blower from a forage harvester. It was hoped that these precision-cut components would improve capacity, power requirements, and particle-size distribution. With this design, stover exiting the threshing cylinder and cleaning shoe was gathered with a converging auger which fed the material into the modified components from a Hesston model 7155 forage harvester (fig. 1). Design details can be found in Hoffman (2008). The theoretical length-of-cut (TLC) was adjustable between 11 and 20 mm. A recutter screen with 76 mm square opening could be placed behind the cutterhead to further size-reduce the stover if desired. Material was discharged from the blower into a spout that concentrated the crop stream and directed the stream to a trailing wagon. The stover processor was designed to be easily removed so that two-pass harvesting configurations could be investigated (fig. 2). When the stover processor was removed, the material –other-than-grain (MOG) exiting the convergence auger would be directed on top of the windrow formed by modified corn head or was placed directly to the ground as desired.

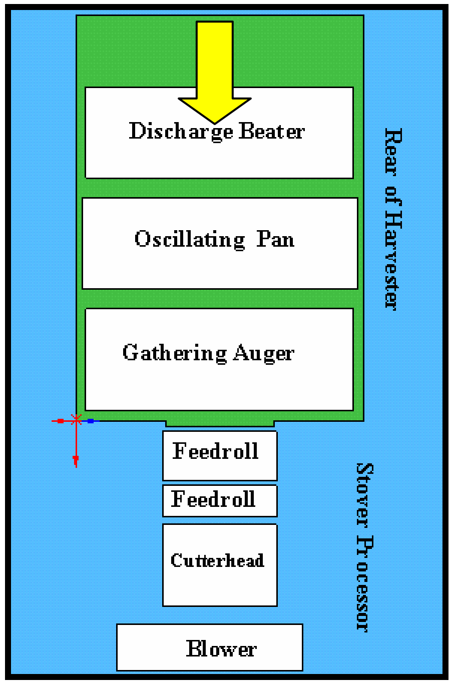

Figure 1. Schematic top-view layout of the rear combine and stover processor. Arrow indicates the material direction through the sequenced material handling components.

DESCRIPTION OF HARVESTER HEADS

Three different heads were used to harvest different stover fractions. First, a John Deere model 693 ear-snapper corn head was used without modification to capture the ear plus some portion of the top stalk. Next, a John Deere model 666R whole-plant corn head normally intended for use with a forage harvester was adapted to the combine harvester to capture the whole-plant. When the stover processor was in place, both heads could be used in the single-pass configuration. With the stover processor removed, the harvester with the ear-snapper head was considered the control configuration. When the combine was configured without the stover processor, the whole-plant head could be used to form windrows of stover by passing the whole-plant through the combine.

The final head configuration involved a modified Slavutich model KMM-6 ear-snapper corn head. As originally configured, this corn head not only snapped the ears but to also gathered, size-reduce and transported stalks and leaves into a wagon pulled alongside the head (Shinners et al., 2009a). For this research, modifications were made to this head so that it formed windrows of stalks and leaves. The cutterhead, blower and spout were removed and the gathering auger re-configured so that material was conveyed to the center of the head. An opening was made at the rear of the auger trough so that material was discharged from the auger onto the ground directly under the combine feederhouse (fig. 3). The MOG were then placed on top of the windrow as this material was ejected from the rear of the combine (fig. 2).

Figure 2. Combine harvester configured to harvest stover in single-pass using precision-cut stover processor (top) or to harvest stover in two-passes by forming stover windrows during grain harvest (bottom). Note that MOG exiting the rear of the combine was placed on top of the windrow formed by the stalk-gathering head.

Figure 3. View from rear of stalk-gathering head showing discharge for the ear gathering auger (top) and discharge of stalk gathering auger (bottom). Ears were fed into the combine feederhouse and stalks were formed into a windrow on the ground underneath the feederhouse.

EXPERIMENTS CONDUCTED

Replicated block field experiments were performed at the Arlington Agricultural Research Station (AARS) of the University of Wisconsin (UW) using a typical corn grain variety and the combine configurations outlined in table 1. Each experimental treatment was replicated five times per day. All stover windrows were harvested with a John Deere model 7800 self-propelled forage harvester (SPFH) equipped with a model 630A windrow pick-up.

During performance experiments, the ground speed of the combine harvester was altered to load the engine to approximately 2250 rpm to maintain similar machine loadings across all treatments. The speed of the threshing cylinder and the cleaning fan were approximately 360 and 970 rpm, respectively. Time to harvest each plot and the distance traveled were recorded to calculate the ground speed, and stover and grain mass-flow rates. Stubble heights were taken in 15 random locations in each plot. A wagon equipped with load cells was pulled behind the combine harvester or the SPFH to collect and weigh the harvested stover. A grain cart, also equipped with load cells, was used to weigh the harvested grain. The load cells could determine the mass to the nearest 2 kg on either collection implement. Three stover sub-samples were taken from each replicate test to determination of moisture, ash, and grain content, and particle-size. Three sub-samples of grain were taken from each replicate test for determination of moisture and stover content. All the stover moisture content samples were oven dried at 103° C for 24 hours (ASABE Standard S358.2; ASABE 2008) and the grain moisture content samples were oven dried for

72 hours at 103°C (ASABE Standard S352.2; ASABE 2008). Stover particle-size was determined using ASABE Standard S424.1 (ASABE, 2008). Grain in stover or stover in grain mass fractions were determined by hand sampling representative sub-samples and oven drying each fraction. A line transect method (30 m string with markers at 30 cm spacing laid across the rows at a 45° diagonal) was used to quantify ground cover in two locations after harvest of each plot (Al-Kaisi et al., 2003).

Table 1. Single-pass, two-pass and control combine harvester configurations; harvest dates; and range of crop conditions during field experiments conducted in 2007 and 2008.

Combine Configuration	Combine Head	Targeted Stover Fractions		Target Combine Head Height	Combine Stover Processor
		Cob/husk	Stalk/leaves	cm	Used
Single-pass	Ear-snapper	X		60	X
" " .	Whole-plant	X	X	25, 50	X
Two-pass[a]	Stalk-gathering	X	X	25, 50	
" " .	Whole-plant[b]	X	X	25	
Control[c]	Ear-snapper	X	X	60	
		2007[d]	2008[e]		
Replicate Harvest Dates		10/18, 22, 25 and 11/7	10/16 and 11/5		
Range of Crop Conditions					
Attached Ear Height .. cm		125 - 130	100 - 110		
Drooped Ear Height .. cm		95 - 100	85 - 100		
Grain Moisture .. % w.b.		21.6 - 15.1	27.9 - 22.5		

[a] In 2008, only 25 cm was used.
[b] This configuration only used in 2008.
[c] To windrow stover after grain harvest, the stover was shredded with a Balzer model 1500 flail shredder and then raked with a Kuhn model GA7301 rotary rake.
[c] Corn was Renk 689 YGP with 106 day CRM planted on May 2, 2007.
[d] Corn was Pioneer 34A20 with 109 day CRM planted on May 6, 2008.

Unharvested cobs were quantified from the two-pass and control plots after the stover had been harvested. Cobs were hand collected in 12 random plots per treatment (1.8m long by 4.6m wide – i.e. across all harvested rows). The cobs were oven dried and weighed, and the data reported as dry mass per unit area.

Strain gauges, fuel flow meters, and speed sensors were used to further quantify the combine harvester's performance (Hoffman, 2008; Shinners et al., 2009a). Strain gauge and speed sensors were located in the drive shaft of the rear stover processor and in the main driveshaft to the combine corn head. The torque and speed signals were captured at 10 Hz by a computer using a LabView data acquisition system. The measured torque and speed allowed power for stover gathering and processing to be calculated.

STATISTICAL ANALYSIS

Statistical analyses were done using single-factor or two-factor analysis of variance where appropriate. Two-factor analysis of variance was used when confounding effects, such as experiments replciated over several days, could be removed by blocking. The least significant difference (LSD) method was used to rank results (Steel et al., 1996).

RESULTS

STOVER YIELD AND MOISTURE

In 2007 and 2008, the stover yield for the single-pass system using the ear-snapper head was much lower then the yield produced by the other harvesting systems (tables 2 and 3). This was expected and consistent with previous work (Shinners et al., 2007c; 2009a) because only the cob, husk, and some of the top of the stalks are captured by the ear-snapper head. If grain yield can be considered approximately equal to stover yield (Shinners and Binversie, 2007a), then use of the ear-snapper head only captured 20% of the theoretical available stover. Harvesting with this head left 7.8 Mg DM/ha of stover residue which was why ground cover was greatest for this harvester configuration (table 2 and 3).

Single-pass harvesting of the whole plant produced the highest yield of stover, capturing 62 and 69% of the theoretical available stover at the high and low cut height, respectively (tables 2 and 3). Harvesting with this head left a two-year average of 3.2 Mg DM/ha of stover residue which was why average ground cover was the lowest for this configuration. Averaged over the two years, there was a 16% reduction in yield from the low to high cut height. In 2007, drying conditions were typical and cutting high reduced stover moisture by almost 5 percentage units. In 2008, drying conditions were poor and cutting height had small influence on stover moisture.

Table 2. Moisture and yield of stover and grain fractions, unharvested cob, and ground cover for experiments conducted in 2007.

Harvest System and Head Type	Ratio of Cut to Ear Height	Moisture .. % w.b.		Stover Harvest Yield		Grain Harvest Yield		Unharvested Cob	Ground Cover
		Stover	Grain	Mg WM / ha	Mg DM / ha	Mg WM / ha	Mg DM / ha	kg DM / ha	%
Single-pass[a]									
Ear-snapper	0.37	24.7c	18.9c	2.7a	2.0a	11.6c	9.4c	---	78c
Whole-plant									
Low cut	0.22	41.4e	19.7d	10.6e	6.1e	10.7b	8.6ab	---	41a
High cut	0.40	36.7d	19.6d	8.7d	5.5de	10.9b	8.8ab	---	45a
Two-pass[b]									
Stalk-gathering									
Low Cut	0.18	22.1bc	15.1a	6.1c	4.8cd	10.0a	8.5a	117a	63b
High Cut	0.30	20.6ab	14.9a	5.7bc	4.5bc	10.5ab	9.0bc	156a	65b
Multi-pass[c]									
Ear-snapper	0.43	17.3a	15.4a	4.6b	3.8b	11.1c	9.4c	688b	67b
LSD[d] (P=0.05)		3.4	0.6	1.1	0.9	0.5	0.4	376	10

[a] Single-pass harvesting involves simultaneous harvest of grain and stover with the modified combine. Theoretical-length-of-cut of the stover processor was 16 mm.
[b] Two-pass harvesting involves first pass to harvest grain with combine harvester and second pass to harvest stover with SPFH. Theoretical-length-of-cut of the SPFH was 6 mm.
[c] Control configuration with first pass using ear-snapper head to harvest grain followed by stover harvest by flail shredding, raking and chopping with SPFH.
[d] Mean values followed by different letters in the same column are significantly different at 95% confidence.

Table 3. Moisture and yield of stover and grain fractions, unharvested cob, and ground cover for experiments conducted in 2008.

Harvest System and Head Type	Ratio of Cut to Ear Height	Moisture .. % w.b.		Stover Harvest Yield		Grain Harvest Yield		Unharvested Cob	Ground Cover
		Stover	Grain	Mg WM / ha	Mg DM / ha	Mg WM / ha	Mg DM / ha	kg DM / ha	%
Single-pass[a]									
Ear-snapper									
With Recutter	0.40	41.4ab	25.9	3.1a	1.8a	13.4	9.9	---	88d
Without Recutter	0.39	42.2abc	26.3	3.1a	1.7a	12.8	9.4	---	84d
Whole-plant									
Low Cut	0.22	44.5abc	24.4	11.9d	6.5c	12.9	9.7	---	47a
High Cut	0.47	47.1bc	26.5	11.8d	5.9c	13.1	9.6	---	56b
Two-pass[b]									
Stalk-gathering	0.31	37.8a	24.5	6.8b	4.1b	13.2	9.9	73a	71c
Whole-plant	0.24	49.2c	24.1	10.0cd	4.8b	13.2	10.0	399b	74c
Multi-pass[c]									
Ear-snapper	0.33	47.6bc	24.6	9.3c	4.6b	13.3	10.0	796c	67c
LSD[d] (P=0.05)		7.2	3.1	2.0	1.0	1.1	0.8	158	8

[a] Single-pass harvesting involves simultaneous harvest of grain and stover with the modified combine. Theoretical-length-of-cut of the stover processor was 16 mm.
[b] Two-pass harvesting involves first pass to harvest grain with combine harvester and second pass to harvest stover with SPFH. Theoretical-length-of-cut of the SPFH was 6 mm.
[c] Control configuration with first pass using ear-snapper head to harvest grain followed by stover harvest by flail shredding, raking and chopping with SPFH.
[d] Mean values followed by different letters in the same column are significantly different at 95% confidence.

The two-pass configuration with the stalk-gathering head performed well, producing well formed stover windrows at high ground speeds (fig. 2). In 2007, stover DM yield was 18% and 26% greater for the stalk-gathering head at its high and low cut heights, respectively, compared to the control multi-pass configuration (table 2). Operating height of the stalk-gathering head did not statistically affect stover yield, although yield tended higher for lower operating height. In 2008, stover yield with the stalk-gathering head was 11% less than the control configuration (table 3). Initial stover moisture was greater in 2008 than 2007 and it was observed that the wetter stalks were not as well cut from the roots by the knife rotor, leaving too much stalk in the field. The average stover yield as 28% less using the two-pass stalk-gathering system compared to the single-pass whole-plant approach. Another approach to two-pass harvesting used the whole-plant head with no stover processor. Here, the entire plant was processed through the combine, with the stover forming a windrow at the combine exit. This approach produced a 17% greater yield than with the stalk-gathering configuration (table 3) due to better yield of the bottom portion of the stalk. The two-pass systems generally had lower harvested stover moisture than other treatments because some field wilting occurred between grain and stover harvest (table 2 and 3).

Cobs are the most desirable fraction of stover biomass because they have high density, good glucose content, comparatively high energy content and low amounts of nitrogen, sulfur and ash (Halvorson and Johnson, 2009). The harvest index for cob has been estimated at 15% of grain yield (Shinners and Binversie, 2007a), so theoretical cob yield was 1350 and 1500 kg DM/ha in 2007 and 2008, respectively. All single-pass configurations captured the entire cob fraction. The two-pass system which used the stalk-gathering head had greater cob yield than the conventional multi-pass system because cobs were placed on the top of the windrow of stalks and leaves (table 2 and 3). Cob harvest efficiency with this system averaged 94% over the two-years of this study, compared to an average of 48% with the conventional multi-pass system. Cob harvest efficiency was 73% with the two-pass system configured with the whole-plant head because the cobs were intermingled within the windrow, rather than being placed on top of the windrow, so some cobs were lost from the bottom of the windrow.

Ground cover was similar for all two-pass treatments and well above the minimum level recommended of 35% cover (USDA-NRCS, 2003). The single-pass system using the ear-snapper head had the greatest ground cover because only the cob and husk were harvested. The single-pass system with the whole-plant head had the least ground cover and in 2007 the ground cover approached the minimum threshold of 35% when harvesting took place at the lowest cut height.

PRODUCTIVITY

Compared to the control configuration with the ear-snapper head, the addition of the stover processor reduced combine area productivity by 7% averaged across the two-years of the study (table 4 and 5). The two-pass configuration with stalk-gathering head reduced combine area capacity by an average of 9%. This small loss in productivity is important because grain will remain the economic driver in the decision as to how corn will be harvested. It is widely expected that producers will want to preserve their harvesting ability of the grain fraction and not interfere significantly with the speed of grain harvest. Processing the whole-plant through the combine to form a windrow decreased the area productivity of the combine by 25% compared to the control configuration (table 5). The difference in productivity between the stalk-gathering and whole-plant two-pass configurations, which produce nearly the same end product of windrowed stover, shows the advantages of producing the stover windrows by not sending the stalk and leaves through the threshing and separation systems.

The previous design of the single-pass harvester used a flail chopper as the stover processor. When configured with the whole-plant head, the area productivity was 1.4 ha/h or a 56% reduction from the control (Shinners et al., 2009a). The change from the flail chopper to the precision-cut stover processor helped increase area productivity to an average of 2.2 ha/h, an improvement of 57% (tables 4 and 5). The productivity of the single-pass harvester with whole-plant head was 45% and 33% less than the control in 2007 and 2008, respectively. The improvement in performance was mainly due to modifications made to improve material flow to the stover processor from the rear of the threshing, separation and cleaning systems (Bennett, 2009). Nonetheless, harvesting, size-reducing and transporting stover in this fashion reduced grain harvest productivity by an average of 39% compared to conventional practices, which is the major drawback of harvesting stover in a single-pass.

The SPFH had almost twice the engine power of the combine harvester, yet the stover mass-flow-rate of the SPFH averaged only 28% greater than that of the combine in the single-pass whole-plant configuration (tables 4 and 5). There were two potential reasons for this result. First, the ability of the windrow pick-up of the SPFH to feed the windrows to the feed rolls greatly limited ground speed. Second, no merging of windrows occurred before harvest. The low windrow density combined with limited ground speed due to pick-up performance resulted in much less than expected stover mass-flow-rates from the SPFH.

Table 4. Stover and grain mass flow rates, and area productivity for the different combine harvester configurations and stover harvesting methods for harvesting corn grain and stover in 2007.

Harvest System and Head Type	Ratio of Cut to Ear Height	Stover Mass Flow[e] Mg/h		Grain Mass Flow - Combine Mg/h		Area Productivity ha/h	
		WM	DM	WM	DM	Combine	SPFH
Single-pass[a]		Combine					
Ear-snapper	0.37	7.6a	5.7a	32.4c	26.2c	2.8b	
Whole-plant							
Low cut	0.22	18.2bc	10.4b	18.2a	14.6a	1.7a	
High cut	0.40	19.2bc	12.0bc	23.6b	18.9b	2.2a	
Two-pass[b] Stalk-gathering		SPFH					
Low cut	0.18	20.3c	15.7d	32.4c	27.5c	3.2bc	3.4
High cut	0.30	20.9c	16.6d	34.4c	29.3c	3.3bc	3.7
Multi-pass[c]							
Ear-snapper	0.43	15.7b	13.8cd	40.4d	34.2d	3.6c	3.5
LSD[d] (P=0.05)		3.7	2.8	4.7	3.8	0.5	0.8

[a] Single-pass harvesting involves simultaneous harvest of grain and stover with the modified combine harvester. Theoretical-length-of-cut of the stover processor was 16 mm.
[b] Two-pass harvesting involves first pass to harvest grain with combine harvester and second pass to harvest stover with SPFH. Theoretical-length-of-cut of the SPFH was 6 mm.
[c] Control configuration with first pass using ear-snapper head to harvest grain followed by stover harvest by flail shredding, raking and chopping with SPFH.
[d] Mean values followed by different letters in the same column are significantly different at 95% confidence.
[e] Stover mass flow through the combine for single-pass treatments and through the SPFH for the two-pass and multi-pass treatments

Table 5. Stover and grain mass flow rates, and area productivity for the different combine harvester configurations and stover harvesting methods for harvesting corn grain and stover in 2008.

Harvest System and Head Type	Ratio of Cut to Ear Height	Stover Mass Flow[e] Mg/h		Grain Mass Flow - Combine Mg/h		Area Productivity ha/h	
		WM	DM	WM	DM	Combine	SPFH
Single-pass[a]							
Ear-snapper		Combine					
With Recutter	0.40	10.6a	6.1a	46.5c	34.5b	3.5cd	---
Without Recutter	0.39	11.1a	6.3a	46.7c	34.4b	3.7d	---
Whole-plant							
High Cut	0.47	27.5b	14.0b	32.1ab	23.7a	2.5ab	---
Low Cut	0.40	27.5b	15.2b	30.0a	22.7a	2.3a	---
Two-pass[b]		SPFH					
Stalk-gathering	0.31	25.6b	15.4bc	43.5c	32.8b	3.3c	3.8
Whole-plant	0.24	38.9c	18.7c	35.4b	26.9a	2.7b	3.9
Multi-pass[c]							
Ear-snapper	0.33	37.0c	18.8c	47.3c	35.7b	3.6cd	4.2
LSD[d] (P=0.05)		6.2	3.4	3.9	3.2	0.3	0.5

[a] Single-pass harvesting involves simultaneous harvest of grain and stover with the modified combine harvester. Theoretical-length-of-cut of the stover processor was 19 mm, and recutter screen openings were 76 mm.
[b] Two-pass harvesting involves first pass to harvest grain with combine harvester and second pass to harvest stover with SPFH.
[c] Control configuration with first pass using ear-snapper head to harvest grain followed by stover harvest by flail shredding, raking and chopping with SPFH.
[d] Mean values followed by different letters in the same column are significantly different at 95% confidence.
[e] Mass flow rate of stover harvested by the combine or the SPFH, respectively.

STOVER PHYSICAL PROPERTIES

No matter which single-pass or two-pass configuration was used, the mean particle-size was always much longer than the TLC (tables 6 and 7). This was due to the unfavorable orientation of material entering the feedrolls of either the stover processor on the combine or the SPFH. Stalks showed no evidence of the favorable alignment typically observed with whole-plant corn silage, rather they were observed to be randomly oriented similar to that seen with windrowed crops. The two-pass systems where the stover was size-reduced with the SPFH always produced a smaller mean particle-size than the single-pass systems because a smaller TLC used on the SPFH (5–6 vs. 16–19 mm). It was not feasible to reduce the TLC on the combine stover processor because doing so would have further reduced grain harvesting rate due to power limitations (Shinners et al., 2009a).

The use of the recutter screen produced a 70% reduction in the mean particle-size of the cob/husk stover and with this reduction, the bulk density of the material increased by 71% (table 7). The recutter screen almost halved the amount of uncut husk as quantified by material retained on the top two screens of the particle separator (long fraction). Material density in the wagon was positively correlated with shorter TLC, smaller particle-size and greater mass fraction of cob. The cob has greater particle density than the rest of the stover (Savoie et al., 2004). No configuration achieved 240 kg/m^3, the maximum density typically limited by road transport weight and volume regulations.

Grain in the harvested stover would be considered a loss. Hoffman (2008) reported grain made up 6.0% and 8.2% of the harvested stover mass when the combine was configured with the flail chopper and the ear-snapper and whole-plant heads, respectively. The change to the precision-cut stover processor improved air and material flow at the rear of the combine so only the single-pass system with the whole-plant head had grain loss to the stover greater than 1% of DM (table 7). The two-pass systems had significantly lower loss of grain to the stover than with the single-pass systems (tables 6 and 7).

Foreign material in the grain sample can cause a price dockage because this material complicates grain drying and hinders air flow through stored grain. Despite the large quantity of MOG flowing through the combine with the single-pass configurations, the mass fraction of stover in the grain averaged less than 1% of DM for all configurations (tables 6 and 7). USDA standards for No. 2 yellow corn specify that a sample can have no more than 3% broken grain or foreign material (USDA, 2009).

Ash content is an important material property. High inorganic content, as measured by ash, reduces the amount of usable feedstock in a bioreactor and impairs process efficiency. Inorganic material will most likely need to be shipped back to the feedstock production site, further challenging the economics and energy balance of corn stover as a feedstock. There was no significant difference in ash content between single-pass and two-pass harvesting schemes (table 10). Ash content tended higher with the two-pass system because stover was harvested from the ground with the SPFH windrow pick-up, which likely gathered some soil with the stover. The shredding and raking operations gathered significantly more soil, so the ash content was 66% more than with the two-pass system.

Table 6. Stover particle size, grain located in the stover sample, stover in the grain sample, material density in the wagon, and stover ash content for different combine configurations and harvesting methods for crop harvested in 2007.

Harvest System and Head Type	Ratio of Cut to Ear Height	Stover Particle-size		Grain in Stover	Stover in Grain	Density in Wagon		Ash Content
		Mean mm	Long Fraction[e] %	% of DM	% of DM	kg WM / m^3	kg DM / m^3	% of DM
Single-pass[a]								
Ear-snapper	0.37	48	48	5.2	0.3	77	58	4.1a
Whole-plant								
Low cut	0.22	29	35	5.2	0.8	103	59	4.9a
High cut	0.40	27	36	6.4	0.7	100	61	
Two-pass[a]								
Stalk-gathering								
Low Cut	0.18	12	35	0.6	0.3			6.0b
High Cut	0.30	13	37	0.7	0.5			5.8ab
Multi-pass[b]								
Ear-snapper	0.43	11	31	0.6	0.5			9.8c
LSD[c] (P=0.05)		3	4.0	0.6	0.3			1.8

[a] Single-pass harvesting involves simultaneous harvest of grain and stover with the modified combine harvester. TLC of the stover processor was 16 mm.
[b] Two-pass harvesting involves first pass to harvest grain with combine harvester and second pass to harvest stover with SPFH. TLC of the SPFH was 5 mm.
[c] Control configuration with first pass using ear-snapper head to harvest grain followed by stover harvest by flail shredding, raking and chopping with SPFH.
[d] Mean values followed by different letters in the same column are significantly different at 95% confidence.
[e] Long fraction is the fraction of the total sample mass that resides on the top two sieves of the ASABE Standard S424.2 particle-size separator.

Table 7. Stover particle size, grain located in the stover sample, stover in the grain sample, and material density in the wagon for different harvest methods for crop harvested in 2008.

Harvest System and Head Type	Ratio of Cut to Ear Height	Stover Particle-size		Grain in Stover	Stover in Grain	Density in Wagon	
		Mean mm	Long Fraction[e] %	% of DM	% of DM	kg WM / m^3	kg DM / m^3
Single-pass[a]							
Ear-snapper							
With Recutter	0.40	17a	43a	0.9ab	0.1a	168	96
Without Recutter	0.39	55c	80c	0.5ab	0.1a	98	56
Whole-plant							
High Cut	0.47	43b	74c	2.8c	0.1a	143	73
Low Cut	0.40	42b	74c	1.5b	0.3b	133	73
Two-pass[b]							
Stalk-gathering	0.32	21a	47ab	0.3a	0.1a		
Whole-plant	0.24	24a	51b	0.6ab	0.1a	197	96
Multi-pass[c]							
Ear-snapper	0.23	20a	46ab	0.1a	0.1a	121	74
LSD[d] (P=0.05)		8	6	1.1	0.1		

[a] Single-pass harvesting involves simultaneous harvest of grain and stover with the modified combine harvester. TLC of the stover processor was 19 mm, and recutter screen openings were 76 mm .

[b] Two-pass harvesting involves first pass to harvest grain with combine harvester and second pass to harvest stover with SPFH. TLC of the SPFH was 6 mm.

[c] Control configuration with first pass using ear-snapper head to harvest grain followed by stover harvest by flail shredding, raking and chopping with SPFH.

[d] Mean values followed by different letters in the same column are significantly different at 95% confidence.

[e] Long fraction is the fraction of the total sample mass that resides on the top two sieves of the ASABE Standard S424.2 particle-size separator.

SPECIFIC ENERGY AND FUEL USE

The specific energy of the stover processor should be relatively constant for a given material and TLC. When configured to harvest whole-plant stover with a precision-cut cutterhead, the specific energy for processing stover with the ranged between 4.0 and 4.9 kWh/Mg DM (tables 8 and 9). This is 44 to 48% lower than required when using the fail chopper for stover processing (Shinners et al., 2009a). When configured to harvest mainly cob and husk with the ear-snapper head (no recutter), the specific energy for processing stover with the ranged between 4.6 and 5.3 kWh/Mg DM. The slightly higher specific energy with this material was likely due to expected greater cutting energy required by the stover dominated by the cob. The use of the recutter increased specific energy for stover processing by 70% (table 9). However, this energy expenditure decreased particle-size by 71% and increased bulk density in the wagon by 68% (table 7).

Fuel-use for the combine is a good surrogate measure of the added power required to harvest and process stover because this measurement takes into account the added power requirements to process any additional MOG through the threshing, separation, cleaning, and stover processing systems. Average fuel use for the control configuration was 9.0 L/ha. Adding the stover processor to this combine to process and capture primarily the cob and husk increased fuel consumption by 39% to 12.5 L/ha. Harvesting whole-plant stover in a single-pass increased fuel consumption by 133% to 20.9 L/ha.

The stalk-gathering head was essentially identical to the ear-snapper head save for the addition of the stover knife rotor and gathering auger. This configuration required 10% more fuel use than the control due to the extra power required to form the stover windrow with the knife rotor and gathering auger. Specific fuel use was 64% greater than the control when forming a windrow by passing the whole-plant through the combine, or 21% greater than forming a windrow with the stalk-gathering head. This difference could be attributed to the increase in power required to process additional MOG through the threshing, separation and cleaning mechanisms.

The single-pass configuration averaged 6.0 Mg DM/ha stover yield compared to 4.5 Mg DM/ha with the two-pass configuration using the stalk gathering head (tables 2 and 3). The specific fuel consumption averaged 21.0 and 11.1 L/ha for these two configurations, respectively. Although there were differences in the quantity of stover processed, the large difference in fuel consumption shows the penalty for processing so much additional MOG through the combine.

Table 8. Combine fuel use, mass flow rates and specific energy for different combine configurations used to harvest corn grain and stover in 2007.

Harvest System and Head Type	Combine Specific Fuel Use			Combine Mass Flow				Combine Specific Energy			
				Wet		Dry		Wet		Dry	
	Wet	Dry		Header[a]	Rear[b]	Header[a]	Rear[b]	Header[a]	Rear[b]	Header[a]	Rear[b]
	L / Mg [a]		L / ha	Mg WM / h		Mg DM / h		kW-h / Mg WM		kW-h / Mg DM	
Single-pass[c]											
Ear-snapper	0.79a	0.99a	13.5b	40.0ab	7.6a	31.9b	5.7a	0.7b	4.0b	0.9b	5.3
Whole-plant											
Low cut	0.93c	1.35c	23.8d	36.4a	18.2b	25.0a	10.4b	0.5a	2.9a	0.7ab	4.9
High cut	0.86b	1.18b	20.1c	42.8b	19.2b	30.9b	12.0b	0.4a	2.9a	0.6a	4.6
Two-pass[d] Stalk-gathering											
Low Cut	---	---	9.4a	---	---	---	---	---	---	---	---
High Cut	---	---	9.3a	---	---	---	---	---	---	---	---
Multi-pass[e]											
Ear-snapper	---	---	8.1a	---	---	---	---	---	---	---	---
LSD[f] (P = 0.05)	0.60	0.12	2.8	5.2	3.2	3.3	1.9	0.1	0.6	0.2	0.9

[a] Mass of both grain and stover fractions harvested with combine harvester.
[b] Mass of stover harvested from rear of harvester.
[c] Single-pass harvesting involves simultaneous harvest of grain and stover with the modified combine harvester. Theoretical-length-of-cut of the stover processor was 19 mm, and recutter screen openings were 76 mm .
[d] Two-pass harvesting involves first pass to harvest grain with combine harvester and second pass to harvest stover with SPFH.
[e] Control configuration with first pass using ear-snapper head to harvest grain followed by stover harvest by flail shredding, raking and chopping with SPFH.
[f] Mean values followed by different letters in the same column are significantly different at 95% confidence...

Table 9. Combine fuel use, mass flow rates and specific energy for different combine configurations used to harvest corn grain and stover in 2008.

Harvest System and Head Type	Combine Specific Fuel Use			Combine Mass Flow				Combine Specific Energy			
				Wet		Dry		Wet		Dry	
	Wet	Dry		Header[a]	Rear[b]	Header[a]	Rear[b]	Header[a]	Rear[b]	Header[a]	Rear[b]
	L / Mg [a]		L / ha	Mg WM / h		Mg DM / h		kW-h / Mg WM		kW-h / Mg DM	
Single-pass[c]											
Ear-snapper											
With Recutter	0.79ab	1.11a	12.6b	57.1	10.6a	40.7	6.5a	0.6b	4.6c	0.8b	7.8b
Without Recutter	0.75a	1.06a	11.4b	57.9	11.1a	40.8	6.3a	0.6b	2.7b	0.8b	4.6a
Whole-plant											
High Cut	0.81ab	1.27b	19.1d	59.5	27.5b	37.7	14.1b	0.2a	1.7a	0.4a	4.0a
Low Cut	0.87a	1.33b	20.9e	57.5	27.6b	37.9	15.2b	0.3a	2.2ab	0.4a	4.0a
Two-pass[d]											
Stalk-gathering	---	---	12.7b	---	---	---	---	---	---	---	---
Whole-plant	---	---	16.1c	---	---	---	---	---	---	---	---
Multi-pass[e]											
Ear-snapper	---	---	9.8a	---	---	---	---	---	---	---	---
LSD[f] (P=0.05)	0.09	0.11	1.3	7.4	4.5	4.8	2.4	0.1	0.7	0.1	1.1

[a] Mass of both grain and stover fractions harvested with combine harvester.
[b] Mass of stover harvested from rear of harvester.
[c] Single-pass harvesting involves simultaneous harvest of grain and stover with the modified combine harvester. Theoretical-length-of-cut of the stover processor was 19 mm, and recutter screen openings were 76 mm .
[d] Two-pass harvesting involves first pass to harvest grain with combine harvester and second pass to harvest stover with SPFH.
[e] Control configuration with first pass using ear-snapper head to harvest grain followed by stover harvest by flail shredding, raking and chopping with SPFH.
[f] Mean values followed by different letters in the same column are significantly different at 95% confidence.

FUEL USE FOR STOVER HARVEST WITH A SPFH

To compare the single- and two-pass harvesting systems, fuel use for harvesting stover with the SPFH must be considered. SPFH fuel use was not quantified in 2007. In 2008, SPFH fuel use per unit area did not significantly vary no matter what combine or post harvest process was used to make the windrows (table 10). The total specific fuel consumption for harvesting grain and stover using the two-pass configuration with the stalk gathering head and SPFH was 24.8 L/ha or 1.81 L/Mg DM harvested (grain plus stover). The specific fuel consumption for the single-pass system was 1.38 L/Mg DM, or 24% less than the two-pass system. This difference will likely shrink if larger combine heads are used to form larger windrows of stover or if windrows are merged before harvest with the SPFH. The full capacity of the SPFH was never realized during these tests due to small windrows that were formed with a six row combine head and ground speed limitations of the windrow pick-up on the SPFH. The mass-flow rates of the SPFH were well below those typically experienced when harvesting such crops as windrowed alfalfa (Shinners, 2003).

Table 10. SPFH specific fuel consumption for harvesting windrows of stover that were formed using different combine configurations during 2008.

Harvest System and Head Type	SPFH Mass Flow (Mg/h) WM	SPFH Mass Flow (Mg/h) DM	SPFH Specific Fuel Use Wet (L / Mg[a])	SPFH Specific Fuel Use Dry (L / Mg[a])	SPFH Specific Fuel Use L / ha
Two-pass[a]					
Stalk-gathering	25.6	15.4	2.21	3.51	13.7
Whole-plant	38.9	18.7	1.66	3.22	14.5
Multi-pass[c]					
Ear-snapper	37.0	18.8	1.86	3.50	14.2
LSD[d] (P = 0.05)	6.2	3.4	0.75	0.55	2.2

[a] Two-pass harvesting involves first pass to harvest grain with combine harvester and second pass to harvest stover with SPFH. TLC of SPFH was 6 mm.
[b] Control configuration with first pass using ear-snapper head to harvest grain followed by stover harvest by flail shredding, raking and chopping with SPFH. TLC of SPFH was 6 mm.
[c] Averages with different markers in the same column are different at 95% confidence.

DISCUSSION

Moisture content is a major factor when considering alternative systems for storing and transporting biomass. Stover below 20% (w.b.) moisture can be successfully stored in bales and aerobic plies (Shinners et al., 2007b; 2009b). Stover above 25% (w.b.) moisture must be stored anaerobically and preserved by fermentation or by the application of additives to rapidly drop the material pH to 4.0 – 4.5 (Shinners et al., 2009b). However, it is important that the acids produced be compatible with downstream conversion technology and if too much of the cell wall carbohydrates are converted to fermentation acids, this could be considered a loss if the acids could not be converted to useable products.

The transportation of water in the feedstock is inefficient because water does not carry energy and its weight takes up valuable weight capacity, so it is favorable to have low moisture feedstocks. Shinners et al. (2009b) suggested that to meet the goals of achieving pH of 4.0 – 4.5 while minimizing the creation of fermentation acids, stover should be stored anaerobically at 35 to 45% (w.b.) moisture. At the time that corn grain is typically harvested, stover can still contain more than 55% (w.b.) moisture (Shinners and Binversie, 2007a). Single-pass harvesting methods offer no way to field dry stover to this target moisture range. Two-pass harvest systems which windrow the stover at harvest offer some ability to manipulate the stover moisture by field wilting before storage.

Single-pass systems require that two collection vehicles simultaneously work in close proximity to the combine. Unloading grain or stover can only be done from one side because there will be standing crop on the other side that cannot be run over. The two-pass system eliminates this potentially difficult and dangerous logistic situation. With single-pass systems, two sets of collection vehicles will be needed, one for grain and one for stover. Many more stover transport vehicles will be needed because of its low density. With a two-pass system, the SPFH can be configured with a small TLC which was shown to increase transport bulk density. Harvesting stover in a second pass with a SPFH will produce much higher harvesting rates than the single-pass system, resulting in less unproductive time at the bagger or bunk silo. During harvest time, it can be difficult to find labor to transport grain. With the single-pass systems where grain and stover must be transported at the same time, labor shortages could result, driving up wages. Two-pass harvesting can dilute the labor requirement if operators can alternately switch between grain and stover transport.

SUMMARY

To improve the performance of a single-pass combine used to harvest corn grain and stover, the flail chopper used to process the stover was replaced with forage harvester feedroll and cutterhead components. These precision-cut components improved material flow and reduced power requirements which resulted in greater area productivity; reduced specific energy for processing stover; reduced combine fuel consumption; and reduced grain loss. However, the area productivity of the single-pass configuration with whole-plant head was still 39% less than the control harvester configuration.

The two-pass harvesting system with the stalk-gathering head successfully produced stover windrows at the time of grain harvest. Because the cob was placed on top of the windrow at formation, 94% of the available cob was harvested with the two-pass system, compared to 48% for the conventional system which used shredding and raking stover after grain harvest. Because the two-pass system did not involve forming windrows by displacing stover across the ground, the ash content was 40% less than with the conventional stover harvest practice. The area productivity at grain harvest of the two-pass systems was only 9% less than the control combine configuration. Total specific fuel use to harvest grain and stover for the single- and two-pass systems was 1.38 and 1.81 L/Mg DM harvested, respectively. This difference may be reduced in the future if larger windrows are formed to match the capacity of the SPFH. The particle-size of the stover harvested in a second pass with the SPFH was 54% smaller than single-pass stover.

The two-pass system decouples corn grain and stover harvest which simplifies the logistics of handling and transporting the two fractions. The formation of stover windrows at grain harvest allows for manipulation of moisture by field curing and may make packaging in dry bales possible compared to the single-pass system. The two-pass system harvested more of the available cob and had lower ash content than the conventional stover harvest method and required two fewer operations.

ACKNOWLEDGEMENTS

This research was partially sponsored by the University of Wisconsin College of Agriculture and Life Sciences, John Deere Harvester Works, John Deere Technology Center, and the USDA-ARS (Grant No. NRCS 68-3A75-4-137). This research could not have been completed without the assistance of the staff of the Arlington Agricultural Research Station.

REFERENCES

Albert, W.W. and L.E. Stephens. 1969. Stalklage silage harvested with a converted combine. ASAE Paper No. 69-313. ASAE, St. Joseph, MI.

Al-Kaisi, M., M. Hanna, and M. Tidman. 2003. Methods for measuring crop residue. Ames, Iowa; Iowa State University Extension. Available at: www.ipm.iastate.edu/ipm/icm/2002/5-13-2002/cropresidue.html Accessed August 2009

ASABE. 2008. Standards 55th Edition. Standard S318.2: Measuring forage moistures. Standard S424.2: Method of determining and expressing particle size of chopped forage materials by screening. S352.2, Moisture measurement - unground grain and seeds. ASABE, St. Joseph, MI.

Ayres, G.E. and W.F. Buchele. 1971. Harvesting and storing corn plant forage. ASAE Paper No. 71-665. ASAE, St. Joseph, MI.

Ayres, G.E. and W.F. Buchele. 1976. An evaluation of machinery systems for harvesting corn plant forage. ASAE Paper No. 76-1015. ASAE, St. Joseph, MI.

Bennett, R.G. 2009. Design and performance comparison of single- and two-pass corn grain and stover harvesting equipment. Master of Science Thesis, University of Wisconsin – Madison.

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

Burgin, K.H. 1941. Corn and stalk harvester. US Patent 2,385,193.

Halvorson, A.D. and J.M.F. Johnson. 2009. Corn cob characteristics in irrigated central Great Plains studies. Agron J 101:390-399.

Hitzhusen, T.E., S.J. Marley and W.F. Buchele. 1970. Beefmaker II: Developing a total corn harvester. Agricultural Engineering 51:632-634.

Hoffman, D. S. 2008. Design and evaluation of a single-pass corn stover harvesting system. Master of Science Thesis, University of Wisconsin – Madison.

Kass, K.J. 1980. Apparatus and method for harvesting and windrowing corn. US Patent Number 4,182,098

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

Savoie, P., K.J. Shinners and B.N. Binversie. 2004. Hydrodynamic separation of grain and stover components in corn silage. Applied Biochemistry and Biotechnology Vol. 113:41-54.

Schroeder, K.R. and W.F. Buchele. 1969. A total corn harvester. ASAE Paper No. 69-314. ASAE, St. Joseph, MI.

Shinners, K.J. 2003. Engineering of silage harvesting equipment: from cutting to storage structure. In Silage Science and Technology, Agronomy. Monograph No. 42. American Society of Agronomy, Madison, WI.

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.

Shinners, K.J., B.N. Binversie. 2007a. Fractional yield and moisture of corn stover biomass produced in the northern US corn belt. Biomass and Bioenergy. Biomass & Bioenergy. 31(8):576-584.

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: 211–221.

Shinners, K.J., G.S. Adsit, B.N. Binversie, M.F. Digman, R.E. Muck and P.J. Weimer. 2007c. Single-pass, split-stream of corn grain and stover. Transactions of the ASABE. 50(2):355-363.

Shinners, K.J., D.S. Hoffman, G.C. Boettcher, J.T. Munk, R.E. Muck and P.J. Weimer. 2009a. Single-pass harvest of corn grain and stover: performance of three harvester configurations. Transactions of ASABE 52(1):51-60.

Shinners, K.J., A.D. Wepner, R.E. Muck and P.J. Weimer. 2009b. Aerobic and anaerobic storage of single-pass, chopped corn stover. ASABE Paper No. 095654.

Steel, R.G.D., J.H. Torrie and D.A. Dickey. 1996. Principles and Procedures of Statistics: A Biometrical Approach. 3rd ed. New York, NY: McGraw Hill.

USDA-NRCS. 2003. Residue management choices: A guide to managing crop residue in corn and soybeans. Publication No. I-03-00-20M-200-S. Washington, D.C.: USDA-NRCS. Available at: http://clean-water.uwex.edu/pubs/pdf/farm.hiresid.pdf Accessed August 2009.

USDA. 2009. Official United States Standards for Grain – Subpart D – United States Standards for Corn.
http://ecfr.gpoaccess.gov/cgi/t/text/textidx?c=ecfr&tpl=/ecfrbrowse/Title07/7cfr810_main_02.tpl
Accessed August 2009.