SINGLE- AND TWO-PASS CORN GRAIN AND STOVER HARVESTING

K. J. Shinners, R. G. Bennett, D. S. Hoffman

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. The change from the flail chopper to the precision-cut stover processor increased area productivity from 1.4 to 2.2 ha h*$^{-1}$*, decreased specific fuel consumption from 33.4 to 20.9 L ha*$^{-1}$ *and decreased grain lost to the stover from 8.2% to 3.9%. However, the single-pass stover system was still 39% less productive than the conventional grain harvest system, and the system was challenged by difficulties with handling grain and stover at the same time. To overcome these problems, an alternative approach was considered in which 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 header to gather the stalks and leaves and form them into a windrow. The cob and husk were then placed on top of the windrow as this material was ejected from the combine. Because the cob was placed on top of the windrow, 94% of the available cob was harvested, compared to 48% for the conventional system in which stover was shredded and raked 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 that of the conventional harvest system. The total specific fuel consumption to harvest grain and stover for the single- and two-pass systems was 1.38 and 1.81 L Mg*$^{-1}$ *DM harvested, respectively. Harvesting merged windrows increased forage harvester mass flow by 67% and reduced specific fuel consumption by 39%, which decreased the difference in energy input between the single- and two-pass systems. 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 drying and may make packaging in dry bales possible compared to the single-pass system.*

Keywords. *Biomass, Corn grain, Corn stover, Density, Feedstock, Particle size.*

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., 2007a). 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 57% (Prewitt et al., 2007; Shinners et al., 2007a). 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%, although collection of the important cob fraction was low with this system (Shinners et al., 2007a).

A single-pass harvesting system that 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, 1976; Burgin, 1941; Buchele, 1976; Hitzhusen et al., 1970; Schroeder and Buchele, 1969). Shinners et al. (2003) estimated that single-pass harvesting reduced total harvesting costs of grain and stover by 26% compared to conventional grain and stover harvesting systems.

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A single-pass harvester has recently been used to harvest various stover fractions for biomass feedstocks (Shinners et al., 2007b, 2009). The modified combine harvester collected cob and husk when configured with an ear-snapper header or collected stalk, leaf, cob, and husk when configured with a whole-plant header 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 important cob fraction, and low ash content. However, the research identified some shortcomings of the single-pass system. These included reduction in grain harvesting rate, high power consumption, insufficient stover size reduction, and resulting low stover bulk density. The single-pass system also offers no opportunity to manipulate the stover moisture by field curing. Because stover often has greater than 25% (w.b.) moisture, stover harvested in a single pass must be stored anaerobically and preserved by fermentation (Shinners et al., 2011). 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; Straeter, 2010). 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 harvests, eliminating most of the logistics problems of simultaneous harvests. The system also requires fewer modifications to the combine harvester than with the single-pass system 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., 2007b, 2009) to improve productivity, reduce power consumption for stover processing, and reduce stover particle size. Additional objectives were to modify a corn header to allow formation of a windrow of stover at the time of grain harvest and 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 used a flail chopper to size-reduce the stover fractions exiting the combine (Shinners et al., 2007b, 2009). When configured with the flail chopper, the single-pass harvester experienced a number of undesirable performance issues. Most notably, stover tended to recirculate within the flail chopper, leading to plugging and non-uniform particle size distribution. Material recirculation

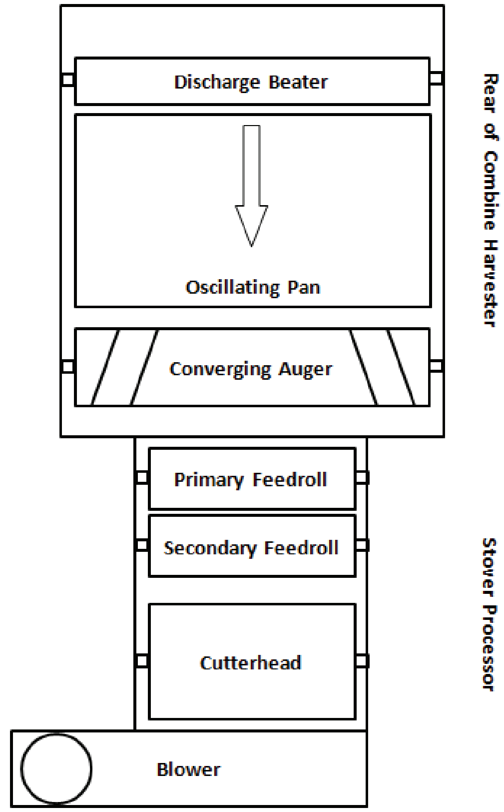

Figure 1. Schematic top view of the rear combine and stover processor. Arrow indicates the direction of material flow through the sequenced material handling components.

also negatively affected capacity because the 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 openings 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 could be directed on top of the windrow formed by the modified corn header or placed directly to the ground as desired.

Description of Harvester Heads

Three different heads were used to harvest different stover fractions. First, a John Deere model 693 ear-snapper corn header was used without modification to capture the

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

ear plus some portion of the top stalk. Next, a John Deere model 666R whole-plant corn header, 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 header was considered the control configuration. Finally, when the combine was configured without the stover processor, the whole-plant header could be used to form windrows of stover by passing the whole-plant through the combine.

The final header configuration involved a modified Slavutich model KMM-6 ear-snapper corn header (JSC Khersonsky Kombayny, Khereson, Ukraine). As originally configured, this corn header not only snapped the ears but also gathered, size-reduced and transported stalks and leaves into a wagon pulled alongside the header (Shinners et al., 2009). For this research, modifications were made to this header so that it formed windrows of stalks and leaves. The cutterhead, blower, and spout were removed, and the gathering auger was reconfigured so that material was conveyed to the center of the header. 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 was then placed on top of the windrow as this material was ejected from the rear of the combine (fig. 2).

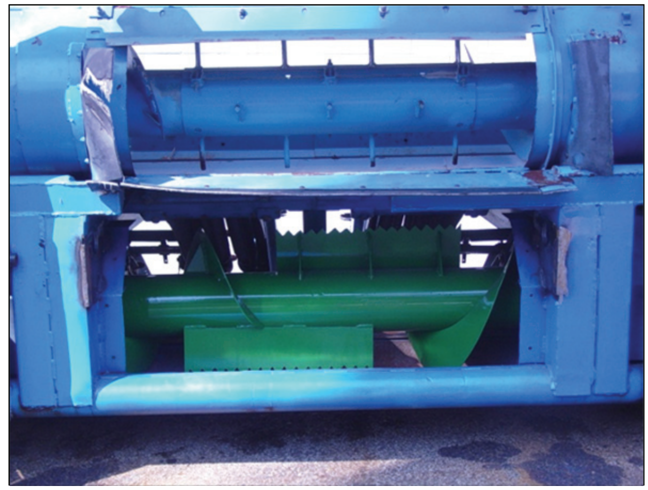

Figure 3. View from rear of stalk-gathering header showing the discharge for the ear-gathering auger (top) and the discharge of the stalk-gathering auger (bottom). Ears were fed into the combine feederhouse, and stalks were formed into a windrow on the ground underneath the feederhouse.

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. The 2007 and 2008 experiments were replicated over four days and two days, respectively. 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 load-

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.

Harvester Configuration	Header Type	Targeted Stover Fractions: Cob/Husk	Targeted Stover Fractions: Stalk/ Leaves	Target Harvest Height (cm)	Combine Stover Processor Used
Single-pass	Ear-snapper	X		60	X
	Whole-plant	X	X	25, 50	X
Two-pass	Stalk-gathering[a]	X	X	25, 50	
	Whole-plant[b]	X	X	25	
Control[c]	Ear-snapper	X	X	60	

	2007[d]	2008[e]
Harvest dates	18 Oct., 22 Oct., 25 Oct., 7 Nov.	16 Oct., 5 Nov.
Range of crop conditions		
Attached ear height (cm)	125 to 130	100 to 110
Drooped ear height (cm)	95 to 100	85 to 100
Grain moisture (% w.b.)	21.6 to 15.1	27.9 to 22.5

[a] In 2008, only 25 cm harvest height was used.
[b] This configuration was 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.
[d] Renk 689 YGP with 106-day comparative relative maturity (CRM) planted on 2 May 2007.
[e] Pioneer 34A20 with 109-day CRM planted on 6 May 2008.

ings 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 the stover and grain mass flow rates. Stubble heights were taken in 15 random locations in each plot. The header harvest height was quantified by the ratio of the stubble height to the attached ear height (table 1). 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 subsamples were taken from each replicate test to determine moisture, ash, and grain contents and particle size. Three subsamples 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 h (*ASABE Standards*, 2008a), and the grain moisture content samples were oven-dried for 72 h at 103°C (*ASABE Standards*, 2008b). Stover particle size was determined using ASABE Standard S424.1 (*ASABE Standards*, 2007). Grain in stover or stover in grain mass fractions were determined by hand-sampling representative subsamples 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).

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 (1.8 m long by 4.6 m wide, i.e., across all harvested rows). The cobs were oven-dried and weighed, and the data are reported as dry mass per unit area.

Strain gauges, fuel flowmeters, and speed sensors were used to further quantify the combine harvester's performance (Hoffman, 2008; Shinners et al., 2009). Strain gauges and speed sensors were located in the drive shaft of the rear stover processor and in the main driveshaft to the combine corn header. 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 either a single-factor or two-factor analysis of variance as appropriate. The two-factor analysis of variance was used when confounding effects, such as trials replicated 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 header was much lower than the yield produced by the other harvesting systems (tables 2 and 3). This was expected and consistent with previous work (Shinners et al., 2007b, 2009) because only the cob, husk, and some of the top of the stalks are captured by the ear-snapper header. If grain yield can be considered approximately equal to stover yield (Shinners and Binversie, 2007), then use of the ear-snapper header captured only 20% of the theoretically available stover. Harvesting with this header left an estimated 7.8 Mg DM ha^{-1} of stover residue, which was why ground cover was greatest with this configuration (tables 2 and 3).

Single-pass harvesting of the whole plant produced the highest yield of stover, capturing 62% and 69% of the theoretically available stover at the high and low cut height, respectively (tables 2 and 3). Harvesting with this header left a two-year average of 3.2 Mg DM ha^{-1} 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, the dry down rate of the standing plant was typical, and cutting high reduced stover moisture by almost five percentage units. In 2008, drying of the standing plant was slowed by environmental conditions, and cutting height had little influence on stover moisture.

The two-pass configuration with the stalk-gathering header 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 header at its high and low cut heights, respectively, compared to the multi-pass control configuration (table 2). Operating height of the stalk-gathering header did not statistically affect stover yield, although yield tended to be greater for the lower operating height. In 2008, stover yield with the stalk-gathering header was 11% less than for the control configuration (table 3). Initial stover moisture was greater in 2008 than in 2007, and it was observed that the wetter stalks were not as well cut from the roots by the knife rotor, leaving more unharvested stalk in the field. The average stover yield was 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 header 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 stover yield than with the stalk-gathering configuration (table 3) due to more complete harvest 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 (tables 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 ratio of cob to grain yield has been estimated at 15% (Shinners and Binversie, 2007), so the theoretical cob yield was 1350 and 1500 kg DM ha^{-1} in 2007 and 2008, respectively. All single-pass configurations essentially captured the entire cob fraction. The two-pass system that used the stalk-gathering header had greater cob yield than the con-

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

Harvester Configuration	Header Type		Ratio of Harvest to Ear Height	Moisture (% w.b.) Stover	Moisture (% w.b.) Grain	Harvested Yield (Mg DM ha^{-1}) Stover	Harvested Yield (Mg DM ha^{-1}) Grain	Unharvested Cob (kg DM ha^{-1})	Ground Cover (%)
Single-pass[a]	Ear-snapper		0.37	24.7 c	18.9 b	2.0 a	9.4 c	--	78 c
	Whole-plant	High cut	0.40	36.7 d	19.6 c	5.5 de	8.8 ab	--	45 a
		Low cut	0.22	41.4 e	19.7 c	6.1 e	8.6 ab	--	41 a
Two-pass[b]	Stalk-gathering	High cut	0.30	20.6 ab	14.9 a	4.5 bc	9.0 bc	156 a	65 b
		Low cut	0.18	22.1 bc	15.1 a	4.8 cd	8.5 a	117 a	63 b
Multi-pass[c]	Ear-snapper		0.43	17.3 a	15.4 a	3.8 b	9.4 c	688 b	67 b
LSD[d] (P = 0.05)				3.4	0.6	0.9	0.4	376	10

[a] Single-pass harvesting involved 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 involved a first pass to harvest grain with a combine harvester and a second pass to harvest stover with a self-propelled forage harvester (SPFH). Theoretical length-of-cut of the SPFH was 5 mm.

[c] The multi-pass control configuration involved a first pass using an ear-snapper header to harvest grain, followed by stover harvest using flail shredding, raking, and chopping with SPFH.

[d] Within each column, means followed by the same letter are not significantly different at the 5% level.

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

Harvester Configuration	Header Type		Ratio of Harvest to Ear Height	Moisture (% w.b.) Stover	Moisture (% w.b.) Grain	Harvested Mass (Mg DM ha^{-1}) Stover	Harvested Mass (Mg DM ha^{-1}) Grain	Unharvested Cob (kg DM ha^{-1})	Ground Cover (%)
Single-pass[a]	Ear-snapper	With recutter	0.40	41.4 ab	25.9	1.8 a	9.9 a	--	88 d
		Without recutter	0.39	42.2 abc	26.3	1.7 a	9.4 a	--	84 d
	Whole-plant	High cut	0.47	47.1 abc	26.5	5.9 c	9.6 a	--	56 a
		Low cut	0.22	44.5 bc	24.4	6.5 c	9.7 a	--	47 b
Two-pass[b]	Stalk-gathering		0.31	37.8 a	24.5	4.1 b	9.9 a	73 a	71 c
	Whole-plant		0.24	49.2 c	24.1	4.8 b	10.0 a	399 b	74 c
Multi-pass[c]	Ear-snapper		0.33	47.6 bc	24.6	4.6 b	10.0 a	796 c	67 c
LSD[d] (P = 0.05)				7.2	3.1	1.1	0.8	158	8

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

[b] Two-pass harvesting involved a first pass to harvest grain with a combine harvester and a second pass to harvest stover with a self-propelled forage harvester (SPFH). Theoretical length-of-cut of the SPFH was 6 mm.

[c] The multi-pass control configuration involved a first pass using an ear-snapper header to harvest grain, followed by stover harvest using flail shredding, raking, and chopping with SPFH.

[d] Within each column, means followed by the same letter are not significantly different at the 5% level.

ventional multi-pass system because cobs were placed on the top of the windrow of stalks and leaves (tables 2 and 3). The ratio of actual to estimated total available cob yield 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 that utilized the whole-plant header and sent the entire plant through the combine. In this case, 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 when harvested with the SPFH.

Ground cover was similar for all two-pass treatments and well above the minimum recommended level of 35% cover (USDA-NRCS, 2003). The single-pass system using the ear-snapper header had the greatest ground cover because only the cob and husk were harvested. The single-pass system with the whole-plant header 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 header, the addition of the stover processor reduced combine area productivity by 7% averaged across the two years of the study (tables 4 and 5). The two-pass configuration with a stalk-gathering header reduced combine area capacity by an average of only 9%, which was not significantly different from the control. Maintaining productivity is important because grain harvest capacity 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 productivity of the grain fraction. 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 bypassing the stover around 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 header, the area productivity was 1.4 ha h^{-1}, a 56% reduction from the control (Shinners et al., 2009). The change from the flail chopper to the precision-cut stover processor helped increase area productivity to an average of 2.2 ha h^{-1}, an improvement of 57% (tables 4 and 5). The productivity of the single-pass harvester with a whole-plant header 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, sepa-

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

Harvester Configuration	Header Type		Ratio of Harvest to Ear Height	Mass Flow Rate[a] (Mg DM h^{-1})		Area Productivity (ha h^{-1})	
				Stover	Grain	Combine	SPFH
Single-pass[b]	Ear-snapper		0.37	5.7 a	26.2 c	2.8 b	--
	Whole-plant	High cut	0.40	12.0 bc	18.9 b	2.2 a	--
		Low cut	0.22	10.4 b	14.6 a	1.7 a	--
Two-pass[c]	Stalk-gathering	High cut	0.30	16.6 d	29.3 c	3.3 bc	3.7 a
		Low cut	0.18	15.7 d	27.5 c	3.2 bc	3.4 a
Multi-pass[d]	Ear-snapper		0.43	13.8 cd	34.2 d	3.6 c	3.5 a
LSD[e] (P = 0.05)				2.8	3.8	0.5	0.8

[a] Stover mass flow through the combine for single-pass treatments and through the SPFH for the two-pass and multi-pass treatments.
[b] Single-pass harvesting involved simultaneous harvest of grain and stover with the modified combine harvester. Theoretical length-of-cut of the stover processor was 16 mm.
[c] Two-pass harvesting involved a first pass to harvest grain with a combine harvester and a second pass to harvest stover with a self-propelled forage harvester (SPFH). Theoretical length-of-cut of the SPFH was 5 mm.
[d] The multi-pass control configuration involved a first pass using an ear-snapper header to harvest grain, followed by stover harvest using flail shredding, raking, and chopping with SPFH.
[e] Within each column, means followed by the same letter are not significantly different at the 5% level.

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

Harvester Configuration	Header Type		Ratio of Harvest to Ear Height	Mass Flow Rate[a] (Mg DM h^{-1})		Area Productivity (ha h^{-1})	
				Stover	Grain	Combine	SPFH
Single-pass[b]	Ear-snapper	With recutter	0.40	6.1 a	34.5 b	3.5 cd	--
		Without recutter	0.39	6.3 a	34.4 b	3.7 d	--
	Whole-plant	High cut	0.47	14.0 b	23.7 a	2.5 ab	--
		Low cut	0.40	15.2 b	22.7 a	2.3 a	--
Two-pass[c]	Stalk-gathering		0.31	15.4 bc	32.8 b	3.3 c	3.8 a
	Whole-plant		0.24	18.7 c	26.9 a	2.7 b	3.9 a
Multi-pass[d]	Ear-snapper		0.33	18.8 c	35.7 b	3.6 cd	4.2 a
LSD[e] (P = 0.05)				3.4	3.2	0.3	0.5

[a] Stover mass flow through the combine for single-pass treatments and through the SPFH for two-pass treatments.
[b] Single-pass harvesting involved 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.
[c] Two-pass harvesting involved a first pass to harvest grain with a combine harvester and a second pass to harvest stover with self-propelled forage harvester (SPFH). Theoretical length-of-cut of the SPFH was 6 mm.
[d] The multi-pass control configuration involved a first pass using an ear-snapper header to harvest grain, followed by stover harvest using flail shredding, raking, and chopping with SPFH.
[e] Within each column, means followed by the same letter are not significantly different at the 5% level.

ration, 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. An improvement in windrow pick-up performance and merging of windrows is required in the future to attain the maximum productivity of the two-pass system.

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. Instead, 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 could be used on the SPFH (5 to 6 mm vs. 16 to 19 mm). It was not feasible to reduce the TLC on the combine stover processor because doing so would further reduce the grain harvesting rate due to power limitations (Shinners et al., 2009).

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). Webster et al.

Table 6. Stover particle size, grain 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.

Harvester Configuration	Header Type		Ratio of Harvest to Ear Height	Stover Particle Size: Mean (mm)	Stover Particle Size: Long Fraction[a] (%)	Grain in Stover (% of DM)	Stover in Grain (% of DM)	Density in Wagon (kg DM m^{-3})	Ash Content (% of DM)
Single-pass[b]	Ear-snapper		0.37	48 c	48 c	5.2 b	0.3 a	58	4.1 a
	Whole-plant	High cut	0.40	27 b	36 ab	6.4 c	0.7 b	61	
		Low cut	0.22	29 b	35 a	5.2 b	0.8 b	59	4.9 a
Two-pass[c]	Stalk-gathering	High cut	0.30	13 a	37 b	0.7 a	0.5 ab		5.8 ab
		Low cut	0.18	12 a	35 ab	0.6 a	0.3 a		6.0 b
Multi-pass[d]	Ear-snapper		0.43	11 a	31 a	0.6 a	0.5 ab		9.8 c
LSD[e] (P = 0.05)				3	4	0.6	0.3		1.8

[a] Long fraction is the fraction of the total sample mass that resides on the top two sieves of the ASABE Standard S424.1 particle size separator.
[b] Single-pass harvesting involved simultaneous harvest of grain and stover with the modified combine harvester. Theoretical length-of-cut of the stover processor was 16 mm.
[c] Two-pass harvesting involved a first pass to harvest grain with a combine harvester and a second pass to harvest stover with self-propelled forage harvester (SPFH). Theoretical length-of-cut of the SPFH was 5 mm.
[d] The multi-pass control configuration involved a first pass using an ear-snapper header to harvest grain, followed by stover harvest using flail shredding, raking, and chopping with SPFH.
[e] Within each column, means followed by the same letter are not significantly different at the 5% level.

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

Harvester Configuration	Header Type		Ratio of Harvest to Ear Height	Stover Particle Size: Mean (mm)	Stover Particle Size: Long Fraction[a] (%)	Grain in Stover (% of DM)	Stover in Grain (% of DM)	Density in Wagon (kg DM m^{-3})
Single-pass[b]	Ear-snapper	With recutter	0.40	17 a	43 a	0.9 ab	0.1 a	96
		Without recutter	0.39	55 c	80 c	0.5 ab	0.1 a	56
	Whole-plant	High cut	0.47	43 b	74 c	2.8 c	0.1 a	73
		Low cut	0.40	42 b	74 c	1.5 b	0.3 b	73
Two-pass[c]	Stalk-gathering		0.32	21 a	47 ab	0.3 a	0.1 a	
	Whole-plant		0.24	24 a	51 b	0.6 ab	0.1 a	96
Multi-pass[d]	Ear-snapper		0.23	20 a	46 ab	0.1 a	0.1 a	74
LSD[e] (P = 0.05)				8	6	1.1	0.1	

[a] Long fraction is the fraction of the total sample mass that resides on the top two sieves of the ASABE Standard S424.1 particle size separator.
[b] Single-pass harvesting involved 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.
[c] Two-pass harvesting involved a first pass to harvest grain with a combine harvester and a second pass to harvest stover with a self-propelled forage harvester (SPFH). Theoretical length-of-cut of the SPFH was 6 mm.
[d] The multi-pass control configuration involved a first pass using an ear-snapper header to harvest grain, followed by stover harvest using flail shredding, raking, and chopping with SPFH.
[e] Within each column, means followed by the same letter are not significantly different at the 5% level.

(2010) reported that bulk density of single-pass stover harvested with an ear-snapper header averaged 42 kg DM m^{-3}, less than reported here. Differences could be attributed to stover size reduction (TLC) and greater particle size.

Grain in the harvested stover is considered a loss. Hoffman (2008) reported that 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 header had grain loss to the stover greater than 1% of DM (table 7). The two-pass systems had significantly lower grain loss to the stover than the single-pass systems (tables 6 and 7).

Foreign material in the grain sample can cause a price reduction because this material complicates grain drying and hinders airflow 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 6). Ash content tended to be 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 used on the multi-pass system gathered significantly more soil, so the ash content was 66% less with the two-pass system.

Specific Energy and Fuel Consumption

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 precision-cut forage harvester components, the specific energy for processing stover was between 4.0 and 4.9 kWh Mg^{-1} DM (tables 8 and 9). This was 44% to 48% less than required when using the fail chopper for stover processing (Shinners

Table 8. Combine specific fuel consumption and energy for different configurations used to harvest corn grain and stover in 2007.

Harvester Configuration	Header Type		Specific Fuel Consumption (L Mg^{-1} DM)	Specific Fuel Consumption (L ha^{-1})	Specific Energy (kWh Mg^{-1} DM) Header[a]	Specific Energy (kWh Mg^{-1} DM) Rear[b]
Single-pass[c]	Ear-snapper		0.99 a	13.5 b	0.85 b	5.34 a
	Whole-plant	High cut	1.18 c	20.1 c	0.60 a	4.63 a
		Low cut	1.35 b	23.8 d	0.73 ab	4.89 a
Two-pass[d]	Stalk-gathering	High cut	--	9.3 a	--	--
		Low cut	--	9.4 a	--	--
Multi-pass[e]	Ear-snapper		--	8.1 a	--	--
LSD[f] (P = 0.05)			0.12	2.8	0.15	0.89

[a] Based on power required by header and dry mass flow rates of both grain and stover fractions. Grain and stover moisture and mass flow rates provided in tables 2 and 4, respectively.
[b] Based on power required by stover processor and dry mass of stover harvested from rear of combine.
[c] Single-pass harvesting involved 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 involved a first pass to harvest grain with a combine harvester and a second pass to harvest stover with a self-propelled forage harvester (SPFH).
[e] The multi-pass control configuration involved a first pass using an ear-snapper header to harvest grain, followed by stover harvest using flail shredding, raking, and chopping with the SPFH.
[f] Within each column, means followed by the same letter are not significantly different at the 5% level.

Table 9. Combine specific fuel consumption and energy for different configurations used to harvest corn grain and stover in 2008.

Harvester Configuration	Header Type		Specific Fuel Consumption (L Mg^{-1} DM)	Specific Fuel Consumption (L ha^{-1})	Specific Energy (kWh Mg^{-1} DM) Header[a]	Specific Energy (kWh Mg^{-1} DM) Rear[b]
Single-pass[c]	Ear-snapper	With recutter	1.11 a	12.6 b	0.79 b	7.74 b
		Without recutter	1.06 a	11.4 b	0.76 b	4.59 a
	Whole-plant	High cut	1.27 b	19.1 d	0.34 a	4.02 a
		Low cut	1.33 b	20.9 e	0.48 a	4.03 a
Two-pass[d]	Stalk-gathering		--	12.7 b	--	--
	Whole-plant		--	16.1 c	--	--
Multi-pass[e]	Ear-snapper		--	9.8 a	--	--
LSD[f] (P = 0.05)			0.11	1.3	0.10	1.05

[a] Based on power required by header and dry mass flow rates of both grain and stover fractions. Grain and stover moisture and mass flow rates are provided in tables 3 and 5, respectively.
[b] Based on power required by stover processor and dry mass of stover harvested from rear of combine.
[c] Single-pass harvesting involved 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 involved a first pass to harvest grain with a combine harvester and a second pass to harvest stover with a self-propelled forage harvester (SPFH).
[e] The multi-pass control configuration involved a first pass using an ear-snapper header to harvest grain, followed by stover harvest using flail shredding, raking, and chopping with the SPFH.
[f] Within each column, means followed by the same letter are not significantly different at the 5% level.

et al., 2009). When configured to harvest mainly cob and husk with the ear-snapper header (no recutter), the specific energy for processing stover ranged between 4.6 and 5.3 kWh Mg^{-1} DM. The slightly higher specific energy with this material was likely due to expected greater cutting energy required by the stover dominated by cob. The use of the recutter increased specific energy for stover processing by 70% (table 9). However, this energy expenditure decreased particle size by 70% and increased bulk density in the wagon by 71% (table 7).

Fuel consumption 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, and cleaning systems. Average fuel consumption for the control configuration was 9.0 L ha^{-1}. 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^{-1}. Harvesting whole-plant stover in a single pass increased fuel consumption by 133% to 20.9 L ha^{-1}.

The stalk-gathering header was essentially identical to the ear-snapper header except for the addition of the stover knife rotor and gathering auger. The specific fuel consumption for this configuration was 10% greater than the control due to the extra power required to form the stover windrow with the knife rotor and gathering auger. Specific fuel consumption 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 header. 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^{-1} stover yield compared to 4.5 Mg DM ha^{-1} with the two-pass configuration using the stalk-gathering header (tables 2 and 3). The specific fuel consumption averaged 21.0 and 11.1 L ha^{-1} 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 much more MOG through the combine.

Fuel Consumption for Stover Harvested with the SPFH

To compare the single- and two-pass harvesting systems, fuel consumption for harvesting stover with the SPFH must be considered. SPFH fuel consumption was not

Table 10. Self-propelled forage harvester (SPFH) specific fuel consumption for harvesting windrows of stover formed using different combine configurations during 2008.

Harvester Configuration	Header Type	SPFH Mass Flow ($Mg\ h^{-1}$) Wet Matter	SPFH Mass Flow ($Mg\ h^{-1}$) Dry Matter	SPFH Specific Fuel Consumption Wet Matter ($L\ Mg^{-1}$)	SPFH Specific Fuel Consumption Dry Matter ($L\ Mg^{-1}$)	SPFH Specific Fuel Consumption ($L\ ha^{-1}$)
Two-pass[a]	Stalk-gathering	25.6 a	15.4 a	2.21 a	3.51 a	13.7 a
	Whole-plant	38.9 b	18.7 a	1.66 a	3.22 a	14.5 a
Multi-pass[b]	Ear-snapper	37.0 b	18.8 a	1.86 a	3.50 a	14.2 a
LSD[c] (P = 0.05)		6.2	3.4	0.75	0.55	2.2

[a] Two-pass harvesting involved a first pass to harvest grain with the combine harvester and a second pass to harvest stover with the SPFH. Theoretical length-of-cut of SPFH was 6 mm.
[b] Control configuration with a first pass using an ear-snapper header to harvest grain followed by stover harvest using flail shredding, raking, and chopping with the SPFH. Theoretical length-of-cut of the SPFH was 6 mm.
[c] Within each column, means followed by the same letter are not significantly different at the 5% level.

Table 11. Self-propelled forage harvester (SPFH) specific fuel consumption for harvesting merged windrows of stover formed using the two-pass gathering header.

Number of Windrows Harvested[a]	Mass Flow[b] ($Mg\ DM\ h^{-1}$)	Specific Fuel Consumption ($L\ Mg^{-1}$ DM)	Unharvested Cob ($kg\ DM\ ha^{-1}$)
1	16.3	3.71	
2	20.9	2.75	
3	27.2	2.25	
Cob loss location[c]		After merger	65
		After SPFH	79
LSD[d] (P = 0.05)			66

[a] Number of windrows harvested in single pass with SPFH. Windrows merged with H & S model HSM-12 windrow merger with 3.6 m belt pick-up. Theoretical length-of-cut of the SPFH was 20 mm.
[b] Average stover moisture at harvest was 12.1% (w.b.).
[c] Cob left on ground after merging or after harvest with the SPFH.
[d] Within each column, means followed by the same letter are not significantly different at the 5% level.

quantified in 2007. In 2008, SPFH fuel consumption 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 header and SPFH was 24.8 L ha^{-1}, or 1.81 L Mg^{-1} DM harvested (grain plus stover). The specific fuel consumption for the single-pass system was 1.38 L Mg^{-1} DM, or 24% less than the two-pass system.

A small experiment was conducted to quantify the cob lost by merging windrows and the fuel consumption required to harvest merged stover windrows (table 11). Cob loss from the merger was similar to that experienced with the SPFH. Cob loss from merged windrows harvested with the SPFH was also similar to the cob loss from unmerged windrows. Harvesting merged windrows increased SPFH mass flow by 67% and reduced specific fuel consumption by 39%. Even with the merged windrows, the full capacity of the SPFH was never realized during these tests due to ground speed limitations of the windrow pick-up on the SPFH. The dry mass flow rates of the SPFH were well below those typically experienced when harvesting such crops as windrowed alfalfa (Shinners, 2003). Improvements to the SPFH windrow pick-up to better manage stover windrows are needed.

CONCLUSIONS

Using precision-cut forage harvester components to process stover at the rear of the combine improved performance compared to processing with traditional flail chopper components. The precision-cut processor improved stover material flow, thereby reducing power requirements, fuel consumption, and grain loss. However, when the combine was configured to capture more than 60% of the available stover yield, combine productivity was 39% less than the conventional configuration.

A two-pass harvesting system using a stalk-gathering header successfully produced stover windrows at the time of grain harvest. The two-pass system decoupled grain and stover harvest, simplifying the logistics of handling and transporting the two fractions. Compared to a conventional stover harvest system, the two-pass system harvested more of the available cob, and the stover had less ash, while requiring two fewer field operations. The grain harvest productivity of the two-pass systems was 9% less than that of the conventional combine configuration. Compared to a single-pass system, fuel consumption per unit mass of stover harvested was 31% more for the two-pass system when single windrows were harvested with a forage harvester. However, harvesting merged windrows offset the added fuel consumption of the forage harvester, and this practice has the potential to decrease the total energy input of the two-pass system. Two-pass stover harvesting was a successful alternative system with several beneficial characteristics compared to single-pass or conventional stover harvest systems.

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