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SINGLE-PASS BALING OF CORN STOVER

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Abstract. *A single-pass corn grain and stover harvester was produced by coupling a combine harvester and towed large round baler. An accumulation hopper and metering system was added to the baler to allow for continuous collection of stover through the bale wrapping and ejection cycles. Both the accumulation metering system and the baler were powered hydraulically by the combine. When harvesting with an ear-snapper header at an average of 5.6 ha·h^{-1} and stover collection rate of 1.4 Mg·ha^{-1}, fuel use was increased by an average of 11% over baseline operation without the baler. Bale dry densities of 164 to 206 kg·m^{-3} were achieved in this configuration. The feed system capacity was more than sufficient to handle the mass-flow collected with the ear-snapper header, so the baler and feed system only needed to be operated approximately 38% of the harvest time. When using a whole-plant header to achieve average stover collection rates of 4.5 Mg·h^{-1}, combine area capacity was reduced by more than 50% and the accumulator feed system was less effective at unloading the long stalks collected. Increasing the aggressiveness of the combine residue chopper reduced the hopper unloading time by 69%, but the additional processing of material also increased combine fuel use. Single-pass bales produced at greater than 250 g·kg^{-1} moisture were not well conserved unless stored anaerobically.*

Keywords. *Biomass; baling, cobs; corn stover; density; storage.*

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ABSTRACT

A single-pass corn grain and stover harvester was produced by coupling a combine harvester and towed large round baler. An accumulation hopper and metering system was added to the baler to allow for continuous collection of stover through the bale wrapping and ejection cycles. Both the accumulation metering system and the baler were powered hydraulically by the combine. When harvesting with an ear-snapper header at an average of 5.6 $ha \cdot h^{-1}$ and stover collection rate of 1.4 $Mg \cdot ha^{-1}$, fuel use was increased by an average of 11% over baseline operation without the baler. Bale dry densities of 164 to 206 $kg \cdot m^{-3}$ were achieved in this configuration. The feed system capacity was more than sufficient to handle the mass-flow collected with the ear-snapper header, so the baler and feed system only needed to be operated approximately 38% of the harvest time. When using a whole-plant header to achieve average stover collection rates of 4.5 $Mg \cdot h^{-1}$, combine area capacity was reduced by more than 50% and the accumulator feed system was less effective at unloading the long stalks collected. Increasing the aggressiveness of the combine residue chopper reduced the hopper unloading time by 69%, but the additional processing of material also increased combine fuel use. Single-pass bales produced at greater than 250 $g \cdot kg^{-1}$ moisture were not well conserved unless stored anaerobically.

INTRODUCTION

Corn stover is considered a promising biomass feedstock and alternative animal roughage feed. It consists of all the non-grain fractions of the corn plant, including the cob, husk, leaf, and stalk. When grain moisture is in the typical harvest range of 18-31% moisture, corn stover makes up from 40 to 50% of the above-ground corn plant dry matter (Shinners and Binversie, 2007a). Stover roughly consists of 15% cob, 8% husk, 21% leaf, and 56% stalk by dry mass (Shinners and Binversie, 2007a). Although post-grain harvest of stover is currently practiced to produce roughage feed and animal bedding, there are widely recognized problems with the traditional harvest methods that involve shredding, raking and baling. Prominent among these are too many non-value-added field operations; soil contamination; inconsistent quality; poor timeliness; weather delays; and high costs.

Several decades ago, researchers and machine developers recognized the potential of single-pass harvest of stover and grain in two separate streams, but these machines were not commercialized (Albert and Stephens, 1969; Ayres and Buchele, 1971; Ayres and Buchele, 1976; Burgin, 1941; Buchele, 1976; Hitzhusen et al., 1970; Schroeder and Buchele, 1969). The recently renewed interest in economical harvest of crop residues has revived the development of single-pass corn stover harvest methods (Quick, 2003; Shinners et al., 2007b, 2009, 2012; Webster et al., 2010). These systems involved size-reduction of the stover on the combine harvester with loose, bulk collection in a towed container. This approach has three fundamental issues which hinder adoption: (1) combine productivity is reduced when stover collection rates are great; (2) field logistics are complicated when two separate crop streams must be handled at once; and (3) stover bulk density is low. With these systems, combine productivity may be reduced by 7% to 39% depending on stover collection rate (Shinners et al., 2012). Depending upon the type of size-reduction and fraction of stover collected, bulk density on the collection container ranged from 40 to 100 kg $DM \cdot m^{-3}$ (Shinners et al., 2012).

An attractive alternative to the bulk systems are single-pass baling systems that package the size-reduced stover into large-square bales (Agco, 2011; Glenvar Farms, 2001; Webster et al., 2010). These systems could overcome two of the three major issues with single-pass harvesting. Since bales are dropped in the field at harvest, they can be retrieved after grain harvest is complete, reducing the complication of stover handling during grain harvest. Additionally, the reported bale density of 156 kg $DM \cdot m^{-3}$ (Webster et al., 2010) is greater than the reported density of 40 to 106 kg $DM \cdot m^{-3}$ achieved with the bulk harvest method (Shinners et al., 2009; 2012). The third major issue of bulk single-pass systems is loss of combine productivity. This issue is mainly one of stover collection rate and added combine processing power requirements, which bale systems do not overcome. In fact, large-square balers are quite heavy and require draft power from the combine, so loss of productivity may be exacerbated. Webster et al. (2010) reported decreases in combine productivity of 16%, 39% and 54% when towing a large square baler with stover collection rates of 1.6, 3.4 and 5.4 $Mg \cdot ha^{-1}$, respectively. Large-square balers also require considerable power, so an auxiliary engine on the baler has been required, adding weight and cost to the single-pass system. An alternative single-pass baling system has been developed which utilizes a large-round baler (Keene, 2012). Its potential advantages compared to a towed large-square baler would include lower power requirements so the baler can be powered by the combine without need for an auxiliary engine and less weight which should reduce parasitic draft power.

MACHINE DESCRIPTION

A spout was added at the exit of the residue chopper of a John Deere model 9860STS combine to facilitate collection of the stover leaving the harvester (fig. 1). The spout narrowed the stream from 140 to 76 cm to facilitate material transport from the combine to the baler by concentrating the crop stream and increasing air velocity at the exit. A cap at the spout exit, which pivoted in both the horizontal and vertical planes, was used to direct the crop stream.

When a conventional round bale has reached the desired diameter, crop is typically constrained by circumferentially wrapping the bale surface with twine or net mesh, a process that requires the incoming crop stream to the bale chamber be stopped. Typically this is accomplished by stopping the baler forward motion. When a round baler was applied to a single-pass grain and stover harvester, stopping grain harvest to allow bale wrapping was deemed impractical. Therefore, components were added to a John Deere model 568 round baler to accumulate and hold stover during bale wrapping (fig. 1). The accumulator consisted of a hopper, a conveyor, and a metering system. During unloading, the conveyor moved accumulated material rearward toward the baler where a controlled mat of stover was metered onto the baler pick-up by a rotary metering system. Despite the narrowing of the crop stream by the spout, material was uniformly distributed in the accumulator and side-to-side distribution of stover produced a uniform bale shape. All aspects of the baling, accumulation and hopper unloading sequences were controlled automatically by an electro-hydraulic control system that required little operator input. The accumulator hopper volumetric capacity was sized to collect stover during a 30 s bale wrap cycle at a combine forward speed of 9.6 $km \cdot h^{-1}$ using a 12-row corn header. A stover collection rate of 1.8 Mg $DM \cdot ha^{-1}$ and bulk density of 50 kg $DM \cdot m^{-3}$ were assumed, resulting in a required hopper volume of 2.7 m^3. The baler was powered by a closed-loop hydrostatic drive powered by the combine engine and capable of delivering up to 71 kW peak power. Hydraulic power required by the accumulator conveyor and metering mechanisms was provided by auxiliary hydraulic outlets from the combine. Bales were typically wrapped with four layers of net mesh wrap.

Two types of corn headers were used: ear-snapper (ES) and whole-plant (WP). The ES header was a John Deere model 612C header with stalk chopping rotors. The WP header was a John Deere model 666R header, normally intended for use with a forage harvester, but adapted for use on the combine to increase stover collection rates compared to the ES header. Header drive speed was kept at 500 rpm during experiments, and the target stubble height was 33 and 43 cm for the ES and WP headers, respectively.

Initial tests showed that it was not always necessary to continuously operate the baler and the accumulator conveyor during normal bale formation when harvesting with the ES header. In fact, bale shape and uniformity were positively affected when material was allowed to accumulate in the hopper before being fed to the baler. The baler and accumulator drives were disengaged until the hopper reached about 60% full, at which point the system drives would be reengaged. The hopper was then unloaded to about 80% empty (20% full) and the drives again disengaged. This intermittent operation was referred to as the systems duty cycle.

DATA COLLECTION

The area harvested in each test run was calculated from the width of the header and the distance harvested as measured with a land wheel. The vertical and horizontal diameters on both sides of each bale were measured to the nearest 1 cm and bales were weighed to the nearest 1kg on an 1800 kg capacity platform scale. Bales were radially bored twice from opposite corners to a depth of roughly 50 cm using a 5 cm diameter boring tube. These two subsamples were used for moisture determination by oven drying at 103°C for 24 hours (ASABE Standard S358.2, 2008). The grain harvested during each bale formation was quantified by a grain cart equipped with load cells and recorded to the nearest 2 kg. Two grain subsamples were collected and oven dried at 103°C for 72 hours (ASABE Standard S352.2, 2008) for moisture determination.

The pressure drop across the hydraulic motors used to drive the single-pass baling system was measured at 200 Hz using a SoMat EDAQ data logging system and pressure transducers located at the inlet and outlet of each motor. Theoretical torque required by each motor, ignoring losses, was calculated from motor displacement and the pressure drop across the motor. The speeds of the baler drive and feed components were measured by magnetic speed pickups and were monitored by the baler control system at a high frequency and then collected by the EDAQ logger at a frequency of 5 Hz. The combine had an ISO-11783 conforming CAN bus control area network on which fuel use, engine speed, and ground speed packets were relayed. A Vector GL1000 Compact Logger was used to record the CAN bus packets, which were later decoded to engineering units using the SAE J1939 protocol.

EXPERIMENTS CONDUCTED

Although no formal experimental design was conducted, stover collection rate relative to grain yield and the fraction of collected stover that was cob was quantified from 64 random bales made during the test season. Cob mass was determined by hand fractioning oven dry bore samples from selected bales made using both corn headers. No formal experiment was used to analyze bale density; rather density was compared using bales formed during other experiments. Two baler density setting were investigated by altering the cracking pressure of the relief valve that controls the tension of the baler belts. The high and low settings were maximum relief pressure and the valve opened two turns from maximum, respectively. Density data was analyzed using a one-way analysis of variance, treating each combination of field, header type, and baler density setting as different treatments.

Experiments were performed to analyze the performance of the accumulator unloading system using both header types (tables 1 and 2). With the ES header, a 2^3 randomized blocked design with 4replicates was conducted using residue chopper speed (1600 and 2500 rpm); chopper knife configuration (fully engaged or fully retracted) and accumulator conveyor speed (350 and 400 rpm). By utilizing a fixed harvest distance of 176 m with each replicate test, the hopper was filled to the approximate same volume for each treatment combination. With the WP header, a 2^2 randomized blocked design with 4replicates was conducted using residue chopper speed and knife configuration. Rather than a fixed harvest distance, the hopper was filled to struck-level full volume for each replicate test with the WP header.

Duty cycle was quantified when forming 14 bales using material collected with the ES header (tables 1 and 2). Grain harvest was continuous, but the baler and accumulator drives were disengaged when the hopper was about 60% full and reengaged until the hopper was about 80% empty. The number of accumulator unloading events per bale and time the baler was operating or idle were quantified. The final bale mass was used to calculate the mass unloaded per event and mass-flow-rate to the baler during hopper unloading.

Experiments were performed to quantify the productivity and fuel use of the single-pass harvest system using both header types (table 1 and 2). A 2^2 randomized blocked design was conducted using residue chopper speed (1600 and 2500 rpm); and baler configuration (baler or no baler). Two replicates were used when operating without the baler and four replicates when operating with the baler. Each replicate test represented data collected during the time required to complete a full bale. Ground speed was altered to load the combine engine to 2250 rpm with the ear-snapper header or 2275 rpm with the whole-plant header to maintain similar machine loading across all treatments.

One of the important issues with any single-pass corn stover harvest is stover moisture at the time of harvest. Stover moisture manipulation is not possible with single-pass harvesting so systems to conserve stover value are needed when moisture content is greater than 250 $g \cdot kg^{-1}$. Therefore, storage characteristics were quantified for bales made using the ES header on two different dates to alter the material moisture (tables 1 and 2). Four storage treatments were considered: (1 and 2) wrapped in conventional mesh net – stored outdoors or in closed shed; (3) wrapped in breathable film and stored outdoors; and (4) stored anaerobically in 6 layers of 1-mil stretch plastic film wrap. Bales were removed from storage on 4-April 2012 after 168 and 133 days in storage.

STATISTICAL ANALYSIS

In all cases, the mass is reported on a dry basis. Statistical analysis was performed to determine the least significant differences between sample means of different treatments. Analysis was performed using the Least Squares method in the statistical analysis software JMP 9, (SAS Institute Inc.). For each analysis, a one-way ANOVA across all treatment combinations was performed, and least-significant differences (LSD's) between treatment means were calculated using student t-confidence intervals at a probability of 95%. Designed factorial experiments were additionally pooled by each factor level and analyzed with a multiple-way ANOVA to compare treatment means at the high and low factor levels.

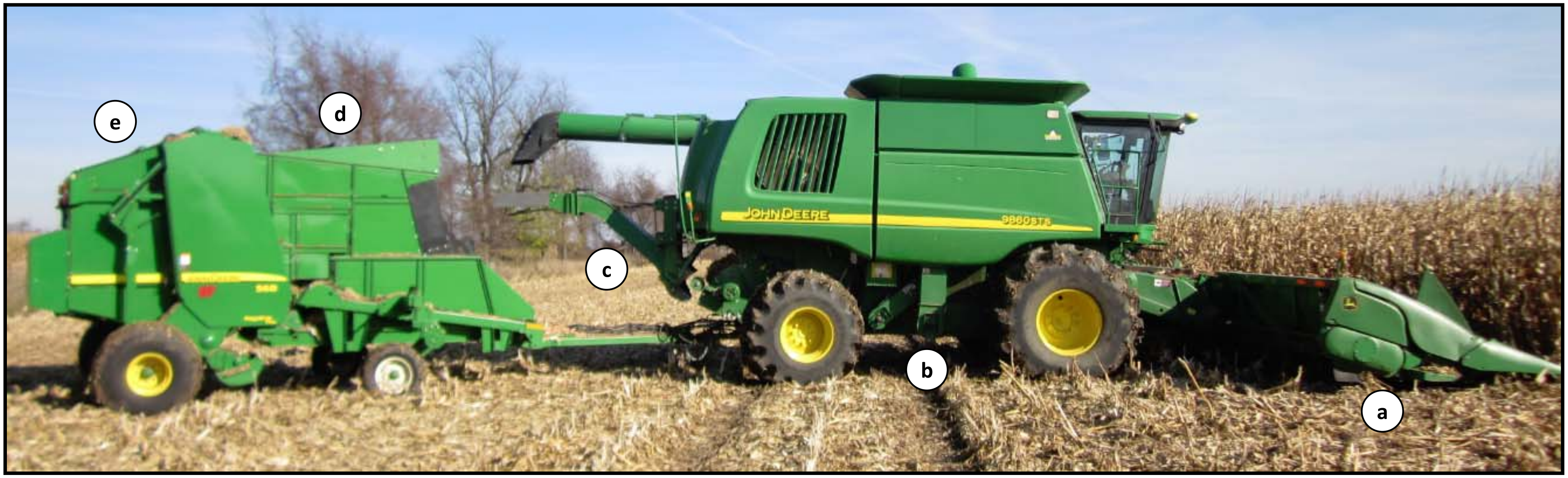

Figure 1. Single-pass corn stover harvesting system consisting of (a) 12-row ear-snapper corn header, (b) grain combine harvester, (c) residue chopper and gathering spout, (d) stover accumulation hopper, and (e) large round baler

Table 1.
Characteristics of crops harvested for machine evaluation tests in 2011.

Field Number	Variety[a]	Planting Dates	Area Harvested [ha]	Grain Yield[b] [Mg-DM/ha]	Harvest Dates	Grain Moisture [w.b.]	Stover Moisture [w.b.]
1	Dairyland 3105Q	9-May	11.9	7.0	12 - 17 Oct.	-	-
					19 Oct.	24%	34%
					23 Nov.	19%	23%
2[c]	Renk 670RR	28-Apr	5.0	9.2	26 - 28 Oct.	19%	41%
					30 - 31 Nov.	19%	35%
3	DeKalb 43 and 52	5-May	14.2	8.9	4 - 5 Nov.	19%	28%
					7 and 18 Nov.	18%	21%
4	Pioneer P0448	5-May	5.3	-	16 - 17 Nov.	18%	26%

[a] Dairyland 3105Q was a silage variety, but was harvested for grain. All other varieties were grain varieties.
[b] Average grain yield harvested by the combine when grain weight and moisture were recorded.
[c] Field was harvested with the whole-plant corn header, increasing the stover yield by capturing more stalks.

Table 2.

Experiments performed during the 2011 harvest season grouped by category.

Experiment[a]	Field[b]	Harvest Dates	Table
Accumulator Feed System Experiments:			
-Hopper unloading rate with ES stover	4	16 - 17 Nov.	5
-Duty cycle	3	4, 7, 18 Nov.	6
-Hopper unloading rate with WP stove	2	30 - 31 Nov.	7
System Fuel Use Experiments:			
-Varied system configurations, WP	2	26 - 28 Oct.	9
-Varied system configurations, ES	3	4 - 5 Nov.	10
Bale Storage Experiments:			
-High moisture stover	1	19-Oct	11
-Low moisture stover	1	23-Nov	"

[a] WP was 6-row whole-plant corn header and ES was conventional 12-row ear-snapping corn header.
[b] Particulars concerning variety and crop conditions are found in table 1.

RESULTS

Stover Properties

Header type and corn variety resulted in different stover collection rates and cob fraction (tables 3 and 4). The WP header collected more than three times as much stover as the ES header and cob made up much less of the total stover mass with the WP header. These results are similar to those reported in Shinners et al. (2012). Corn type significantly affected stover collection rate relative to grain yield with the WP header but not the ES header (table 3). Greater stover collection rates diluted the cob mass in the bales made with the WP header (table 4). With the ES header, the silage type corn resulted in the collection of more non-cob material, presumably because of the greater stalk mass above the ear with corn bred for silage production (table 4).

Table 3.
Ratio of stover mass collected in single-pass bales to harvested grain mass across grain varieties and combine headers.

Field	Corn Variety Type[a]	Combine Header[b]	Stover to Grain Harvested Mass Ratio[c]	
			Average	Std. Dev.
1	Silage	WP	0.61a	0.05
1	Silage	ES	0.17c	0.02
2	Grain	WP	0.47b	0.05
3	Grain	ES	0.16c	0.01

[a] Particulars concerning variety and crop conditions are found in table 1.
[b] WP was 6-row whole-plant corn header and ES was conventional 12-row ear-snapping corn header.
[c] Different letters in the same column group indicate statistically different values from a one-way ANOVA test and student t confidence intervals at $\alpha = 0.05$.

Table 4.
Cob as a fraction of total collected stover mass across fields, varieties, and combine headers. Cob mass determined by hand fractioning bore samples from selected bales.

Field[a]	Corn Variety Type[a]	Combine Header[b]	Cob as a Fraction of Total Stover Mass [% of total DM]
1	Silage	ES	40b
2	Grain	WP	20a
3	Grain	ES	60c
4	Grain	ES	68d
LSD ($\alpha = 0.05$) [c]			4

[a] Particulars concerning variety and crop conditions are found in table 1.
[b] WP was 6-row whole-plant corn header and ES was conventional 12-row ear-snapping corn header.
[c] Least significant difference; different letters in the same column group are statistically different.

Accumulator Performance

Time to unload material collected with the ES header was significantly affected by combine residue chopper speed and knife configuration, and by accumulator conveyor speed (table 5). The time to reach 80% empty was decreased by 3 to 4 s by each variable as it was altered from low to high level and each variable had about the same impact on total unloading time. The time to empty the hopper was almost halved by changing all of the parameters from low to high level. To further examine the relationship between particle size and hopper unloading time, the stalk was hand separated from the harvested stover and a geometric-mean particle length was calculated. The order of stalk geometric-mean particle-length from longest to shortest was 25, 18, 12 and 9 cm for chopper speed/knife configuration settings of low/out, high/out, low/in, high/in, respectively. Stalk particle-length was found to be linearly related to accumulator unloading time (fig. 2). Mass-flow-rate from the accumulator ranged from 12.0 to 22.5 $Mg{\cdot}h^{-1}$ with an average of 16.7 $Mg{\cdot}h^{-1}$. At these unload rates, operation of the accumulator could be intermittent because overall stover mass-flow-rate from the combine with ES header ranged from 7.8 to 8.0 $Mg{\cdot}h^{-1}$ (see table 9).

Time to unload material collected with the WP header was greater than that with ES header (table 6). In addition, mass-flow-rate from the accumulator was less with WP stover due to its lower bulk density. Both of these differences were tied to the greater stalk content and longer particle-length of the WP material. Moving the knives to the fully engaged configuration had the greatest effect, decreasing the WP stover unloading time to 80% and 100% empty by 22 and 39 s, respectively, (47% and 55% reduction) compared to when the knives were retracted.

Increasing the chopper speed resulted in more modest decreases in unloading time of 12 and 22 s (28% and 35% reduction) to the two volumes, respectively. Interaction effects between the two chopper settings were not significant, and the combination of both chopper settings at the high levels reduced the total unloading time by 69% compared to both settings at the low levels. Mass-flow-rate from the accumulator ranged from 3.0 to 9.6 $Mg{\cdot}h^{-1}$ with an average of 6.1 $Mg{\cdot}h^{-1}$. At these unloading rates, even continuous operation of the accumulator could not keep up with the stover mass-flow-rate from the combine which averaged 11.3 $Mg{\cdot}h^{-1}$ (see table 9).

The time required to empty the last 20% of the hopper volume was 39% to 45% and 19% to 36% of the total emptying time for material collected with ES and WP headers, respectively. It was observed that small pieces of stover separated from the bulk mass of accumulated material and were more readily delivered to the baler by the accumulator metering system. Long material, mainly stalk, tumbled many times in the accumulator before passing to the baler near the end of the emptying cycle. Increasing the size of the accumulator and improvements to its metering system to better meter long stalks will be necessary if greater stover collection rates are desired with the single-pass baling system.

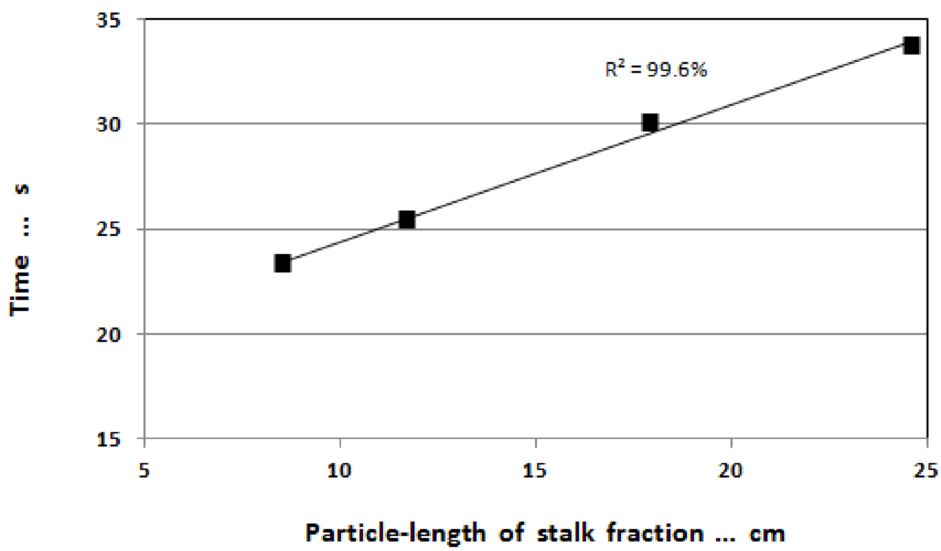

Figure 2. Time to completely empty the accumulator hopper of stover harvested with ear-snapper corn header as a function of geometric-mean particle-length of the stalk fraction (400 rpm hopper conveyor speed).

Table 5
Time to empty the accumulator hopper and stover mass-flow-rate from the hopper after a fixed harvest distance using the conventional 12-row ear-snapping corn header.

System Settings			Hopper Unloading Time		Unloading Rate
Chopper Speed[a]	**Chopper Knives[b]**	**Conveyor Speed[c]**	**To 80% Empty [s]**	**To 100% Empty [s]**	**[Mg·h^{-1}]**
Low	Out	Low	24a	44a	12.0
High	Out	Low	22ab	42ab	12.5
Low	In	Low	21abc	35bc	14.8
High	In	Low	17bcd	29cd	17.8
Low	Out	High	21abc	34c	15.5
High	Out	High	16cd	30cd	17.5
Low	In	High	18bcd	25d	20.7
High	In	High	14d	23d	22.5
	LSD (α = 0.05) [d]		5.1	7.4	-
Chopper	Speed	Low	21a	35a	15.7
		High	17b	31a	17.6
	LSD (α = 0.05)[e]		2	4	-
Chopper	Knives	Out	21a	37a	14.4
		In	17b	28b	18.9
	LSD (α = 0.05)[e]		2	4	-
Conveyor	Speed	Low	21a	37a	14.3
		High	17b	28b	19
	LSD (α = 0.05)[e]		2	4	-

[a] Speed of combine residue chopper; low and high were 1600 and 2500 rpm, respectively.
[b] Stationary knife position in combine residue chopper; out and in were knives completely retracted and fully engaged, respectively.
[c] Speed of unloading hopper on baler accumulator; low and high were 350 and 400 rpm, respectively.
[d] Least significant difference; different letters in the same column group are statistically different.
[e] Data analyzed using a multiple-way analysis of variance and pooled by the given factor level for comparison.

Duty Cycle

When harvesting with the ES header, the accumulator metering system and baler were operated during just over a third of the time required to form a bale (table 7). An average of seven unloading events was required per bale with the average event duration of 16 s. The average time the metering system was engaged and the mass-flow-rate from the accumulator were similar to the averages found in the accumulator unloading tests (table 5). The presence of an accumulator helped maintain grain harvest productivity because for about two-thirds of the time, the only power draw caused by the single-pass baler was overcoming its rolling resistance. The drawbar power for towing the baler loaded with a full bale chamber was measured to be 5.5 and 11.6 kW at 4 and 8 $km \cdot h^{-1}$, respectively (Keene, 2012). If the accumulator metering system was disengaged as the bale neared the selected diameter, then only a small volume of material was unloaded before the initiation of the wrapping process halted unloading. The accumulator volume could then overfill depending on mass-flow-rate from the combine and the wrap cycle time (function of baler rotational speed, bale diameter and number of wraps selected). This situation was overcome by continuously operating the accumulator metering system as the bale neared the selected diameter, insuring a near empty accumulator prior to bale wrapping.

Bale Density

Bale density was significantly greater at the high baler density setting in two of the three fields, with an average increase of 10% (table 8). Overall, stover bales formed with material collected by the ES header had 48% greater density than those formed with WP material, likely due to the greater fraction of bale mass as cob with the ES material (table 3). Bale density was well correlated with the relative fraction of the bale mass that was cob (fig. 3). Bale density can be affected by grain present in the bales; however hand sorting bore samples showed grain content was less than 0.5% by mass.

In general, large square balers produce bales with higher densities than do large round balers, yet the average density observed in field 3 was greater than the average density of 156 $kg \cdot m^{-3}$ reported by Webster et al. (2010) for single-pass large square bales. The density reported by Webster et al. was an average across the different stover collection rates achieved (1.6, 3.4, and 5.4 $Mg \cdot ha^{-1}$). Some of these bales would have had much greater stalk content than the bales made in field 3, where the average collection rate was 1.4 $Mg \cdot ha^{-1}$ and the cob content was 68% by mass. Nonetheless, the average bale density of bales made with both corn headers was 145 $kg \cdot m^{-3}$ which compares favorably with those reported by Webster et al. for large square bales.

Table 6.

Time to empty hopper and stover mass-flow-rate to baler after filling hopper stuck level full using 6-row whole-plant corn header.

High	Out	38b	54b	4.8
Low	In	28c	37bc	6.9
High	In	22c	27c	9.6
LSD (α = 0.05) [c]		7	19	
Chopper	Speed	42a	62a	4.9
		30b	40b	7.2
LSD (α = 0.05)[d]		5	13	
Chopper	Knives	47a	71a	3.9
		25b	32b	8.2
LSD (α = 0.05)[d]		5	13	

[a] Speed of combine residue chopper; low and high were 1600 and 2500 rev/min, respec

[b] Stationary knife position in combine residue chopper; out and in were knives comple

[c] Speed of unloading hopper on baler acumulator; low and high were 350 and 400 rev/n

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[c] Least significant difference; different letters in the same column group are statistically different.

[d] Data analyzed using a multiple-way analysis of variance and pooled by the given factor level for comparison.

Table 7.
Duty cycle summary for the accumulator metering system when harvesting stover collected with the conventional ear-snapper combine header.

	Average	Std. Dev.	Units
Field capacity[a]	5.7	0.3	ha/h
Number of unloading events[a]	6.9	0.7	events/bale
Duty cycle[a]	37	2.3	% of total harvest time[e]
Duration per event[b]	16	4.1	s
Mass unloaded per event[c]	100	-	kg/event
Mass flow rate during unloading[d]	22	-	$Mg{\cdot}h^{-1}$

[a] Averaged across 14 bales.
[b] Averaged across 97 observed metering cycles.
[c] Estimate based on each bale mass and number of cycles used to form the bale.
[d] Estimate based on each bale mass and the cumulative time of metering system operation.
[e] Total harvest time does not include time spent turning at the field headlands, when grain was not harvested and the baler was not in operation.

Table 8.
Average bale densities produced across all tests and settings.

Field	Variety Type[a]	Combine Header[b]	Baler Density Setting[c]	Number of Bales	Bale Dry Density[d] … $kg{\cdot}m^{-3}$ Average	Std. Dev.
1	Silage	WP	Low	4	113e	8
			High	-	-	-
1	Silage	ES	Low	16	122d	7
			High	15	137c	3
2	Grain	WP	Low	21	104f	8
			High	12	120de	8
4	Grain	ES	Low	8	164b	6
			High	-	-	-
3	Grain	ES	Low	13	198a	10
			High	4	206a	8

[a] Particulars concerning variety and crop conditions are found in table 1.
[b] WP was 6-row whole-plant corn header and ES was conventional 12-row ear-snapping corn header.
[c] Baler density relief valve on John Deere 568 baler was fully tightened for the high level and loosened two turns for the low level.
[d] Different letters in the same column group indicate statistically different values based off of a one-way ANOVA test and student t confidence intervals at α = 0.05.

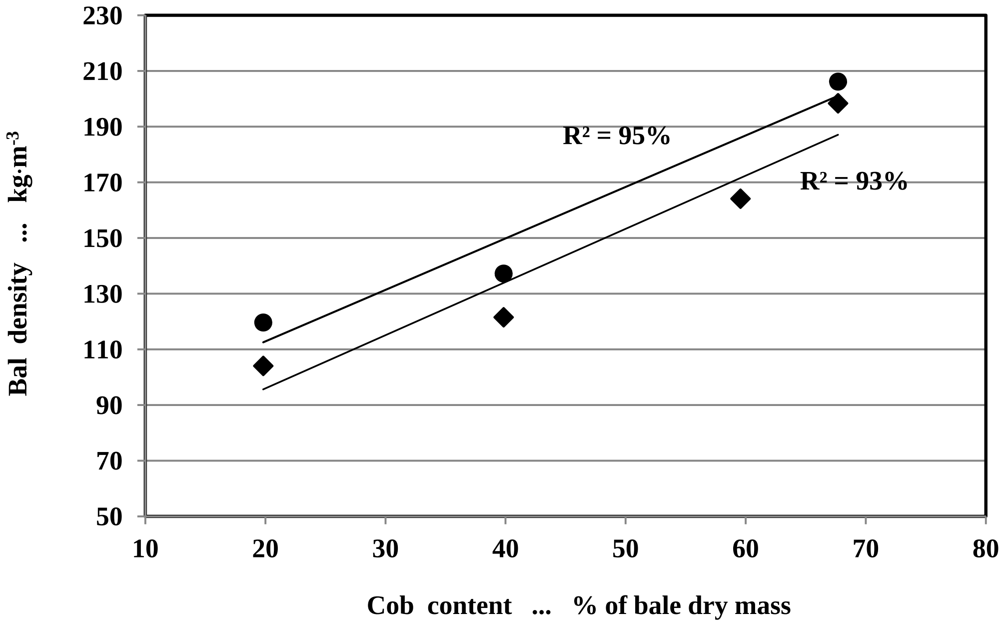

Figure 3. Average dry density of stover bales harvested with ear-snapper corn header as a function of cob content for two density settings (● - high setting; ♦ - low setting).

Combine Productivity and Fuel Use

The addition of the single-pass baler decreased combine productivity by 0.11 ha·h^{-1} or 2% and increased fuel use by 1.2 L/ha or 10%, when harvesting with the ES header (table 9). With intermittent operation of the baler and accumulator metering system, the fuel use associated with the addition of the baler should be more closely tied to the amount of stover collected than with the harvested area. When fuel use was normalized by stover mass collected, use of the baler increased combine fuel use by 0.92 L·Mg^{-1} (11%). Residue chopper speed did not significantly affect area productivity or specific fuel use although operating at high chopper speed numerically increased fuel use by 3%.

Using the WP header increased stover mass-flow-rate by 43% but also resulted in a 45% reduction in combine area productivity compared to harvesting with the ES header (table 10). When harvesting with the WP header, the addition of the single-pass baler decreased combine productivity by 0.22 ha·h^{-1} or 7% and increased fuel use by 3.0 L·ha^{-1} or 12%. Increasing the speed of the residue chopper increased the average fuel use by 0.39 L·Mg^{-1}or 7%.

Webster et al. (2010) reported decreases in combine productivity of 16%, 39% and 54% when towing a large square baler with stover collection rates of 1.6, 3.4 and 5.4 Mg·ha^{-1}, respectively. In this research, combine productivity was reduced 2% and 56% when towing a round baler with stover collection rates of 1.4 and 4.5 Mg·ha^{-1}.

__Table 9.__

Harvest productivity and total combine fuel use when harvesting with ear-snapper corn header, various combine chopper settings and machine configurations.

Machine Configuration[a]		Harvest	Stover Mass	Specific Fuel Use	
Chopper Speed[b]	**Harvest Configuration**	**Rate[c] ha·h^{-1}**	**Flow Rate[d] Mg·h^{-1}**	**L·Mg^{-1} [e]**	**L·ha^{-1}**
Low	No Baler	5.73a	8.4a	8.47c	12.2b
High	"	5.71a	8.4a	8.86bc	12.8ab
Low	SP Baler	5.62b	7.8a	9.36ab	13.5a
High	"	5.61b	8.0a	9.82a	13.8a
		[f]	[f]	[f]	[f]
Baler	No Baler	5.72a	8.4a	8.67b	12.5b
	SP Baler	5.61b	7.9a	9.59a	13.7a
LSD (α = 0.05)[g]		0.11	0.6	0.46	1.5
Chopper Speed	Low	5.67a	8.1a	8.91a	12.9a
	High	5.66a	8.2a	9.35a	13.3a
LSD (α = 0.05)[g]		0.11	0.8	0.44	0.7

[a] Four and two replicates conducted with and without the baler, respectively. All bales were made at low density setting over the distance required to make a full bale of 165 cm diameter.
[b] Speed of combine residue chopper; low and high were 1600 and 2500 rpm, respectively. Chopper knives fully retracted.
[c] Average harvest rate during bale formation; time required to wrap and eject bales not included. Harvest ground speed adjusted to maintain target engine speed of 2250 rpm.
[d] Average harvested stover mass-flow-rate through the combine based on stover collected and harvest duration.
[e] Specific fuel use per stover dry mass; grain mass not included.
[f] Different letters in the same column group indicate statistically different values based off of a one-way ANOVA test and student t confidence intervals at α = 0.05.
[g] Least significant difference; different letters in the same column group are statistically different. Data analyzed using a multiple-way analysis of variance and pooled by the given factor level for comparison.

Table 10.
Total combine fuel use when harvesting with whole-plant header, various combine chopper settings and machine configurations.

Machine Configuration[a]		**Harvest**	**Stover Mass**		
Chopper	**Harvest**	**Rate[c]**	**Flow Rate[d]**	**Specific Fuel Use**	
Speed[b]	**Configuration**	**ha·h^{-1}**	**Mg·h^{-1}**	**L·Mg^{-1} [e]**	**L·ha^{-1}**
Low	No Baler	2.70a	12.1a	5.35c	23.9c
High	"	2.71a	12.1a	5.72bc	25.5bc
Low	SP Baler	2.50b	11.3a	6.02ab	27.1ab
High	"	2.54b	11.3a	6.43a	28.4a
LSD ($\alpha = 0.05$)[f]		0.16	1.2	0.45	2.2
Baler	No Baler	2.70a	12.1a	5.54b	24.7b
	SP Baler	2.52b	11.3a	6.23a	27.7a
LSD ($\alpha = 0.05$)[g]		0.11	0.8	0.3	1.5
Chopper Speed	Low	2.62a	11.7a	5.69b	25.5b
	High	2.60a	11.7a	6.08a	27.0a
LSD ($\alpha = 0.05$)[g]		0.11	0.8	0.30	1.4

[a] Four test replicates at each combination of machine settings. All bales made at low density setting over a fixed harvest distance of 176 which formed a full bale with average bale diameter of 173 cm.
[b] Speed of combine residue chopper; low and high were 1600 and 2500 rpm, respectively. Chopper knives fully engaged.
[c] Average harvest rate during bale formation; time required to wrap and eject bales not included. Harvest ground speed adjusted to maintain target engine speed of 2275 rpm.
[d] Average harvested stover mass-flow-rate through the combine based on stover collected and harvest duration.
[e] Specific fuel use per stover dry mass; grain mass not included.
[f] Least Significant Difference. Different letters in the same column group are statistically different.
[g] Data analyzed using a two-way analysis of variance and then pooled to compare factor level means.

Bale Storage Characteristics

Bales stored aerobically at 350 g·kg^{-1} moisture did not conserve well with average losses of DM during storage of 123 g·kg^{-1} (table 11). These bales lost shape and slumped within days of entering storage and had strong evidence of mold growth at removal from storage. Bales stored aerobically at 230 g·kg^{-1} moisture and stored indoors or wrapped with breathable film were well conserved with average DM losses of 46 g·kg^{-1}. The moisture of bales wrapped in breathable film did not increase appreciably during storage. Bales stored outdoors and uncovered had the greatest DM losses and exposure to precipitation appreciably increased bale moisture during storage. The most effective method of conserving DM was storing the bales anaerobically in stretch plastic film where DM losses averaged only 15 g·kg^{-1}. These results are consistent with those of Shinners et al. (2011) and Shah et al. (2011). When harvest conditions result in single-pass stover moisture greater than 250 g·kg^{-1}., then anaerobic storage will likely be required to conserve stover value.

CONCLUSIONS

The single-pass baler was successful at making well shaped round bales without requiring interruption of grain harvest. Uninterrupted operation was facilitated by an accumulator and metering system where material was collected during the bale wrapping process. The single-pass system achieved 5.6 ha· h^{-1} while collecting stover yields of 1.4 Mg·ha^{-1} at an additional 0.92 L·Mg^{-1} (11%) fuel consumption. Stover bale densities ranged from 164 to 206 kg·m^{-3}, which was greater than other single-pass harvest technologies. When using an ear-snapper corn header, stover collection rates required only intermittent operation of the baler accumulator, decreasing the time the combine had to supply power to round baler.

Harvesting at stover collection rates of 4.5 Mg·ha^{-1} with a whole-plant header reduced area capacity by more than 50% due to the processing requirements in the combine. Difficulties feeding long material from the accumulator further challenged maintenance of area productivity. Additional development work is required to improve combine processing and accumulator unloading rates at greater stover collection rates. Single-pass bales produced at greater than 250 g·kg^{-1} moisture were not well conserved unless stored anaerobically.

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Table 11.
Losses of DM during storage period for stover harvested with ear-snapper corn header on two different dates.

Storage Method[a]	**Moisture Level**[b]	**Moisture Content .. g · kg^{-1}** At Sotrage	**At Removal**	**Storage Losses g · kg^{-1}**
Indoor	High	360a	290c	112ab
Outdoor	High	330a	420a	156a
Breathable Film	High	330a	340 b	103b
Wrapped	High	380a	380ab	20c
LSD (α = 0.05) [c]		50	40	49
Indoor	Low	220a	210c	47a
Outdoor	Low	240a	360a	74a
Breathable Film	Low	220a	250b	46a
Wrapped	Low	240a	240b	9b
LSD (α = 0.05) [c]		30	20	36
Storage	Indoor	290ab	250c	79b
Method	Outdoor	280ab	390a	115a
	Breathable Film	270b	290b	74b
	Wrapped	310a	300b	15c
LSD (α = 0.05) [d]		30	30	33
Moisture	High	350a	350a	105a
Content	Low	230b	260b	44b
LSD (α = 0.05) [e]		20	20	22

[a] "Indoor" indicates bales wrapped in cover-edge net wrap and stored in a closed shed.
"Outdoor" indicates bales wrapped in cover-edge net wrap and stored on sod.
"Breathable Film" indicates bales circumferentially wrapped in a breathable film and stored on sod.
"Wrapped" indicates bales stored anaerobically in stretch plastic film.

[b] Harvest dates were Oct. 19 and Nov. 23 for high and low moisture, respectively. Duration in storage was 168 and 133 days for high and low moisture, respectively.

[c] Least Significant Difference. Different letters in the same column group are statistically different.

[d] Data analyzed using a two-way analysis of variance and pooled to by storage method for comparison.

[e] Data analyzed using a two-way analysis of variance and pooled by moisture content for comparison.

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