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 a towed large-round baler. An accumulation hopper and metering system were 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 rate of 5.6 ha h^{-1} and stover collection rate of 1.4 Mg ha^{-1}, combine 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 with this configuration. The accumulator and feed system capacity were more than sufficient to handle the mass flow collected with the ear-snapper header, so while harvesting grain the baler was only operated for 38% of the total harvest time. When using a whole-plant header to achieve average stover collection rates of 4.5 Mg ha^{-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 size reduction also increased combine fuel use by 7%.*

Keywords. *Baling, Biomass, Cobs, Combine, Corn stover, Density, Grain.*

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 is in the typical harvest range of 18% to 31% moisture, corn stover makes up 40% to 50% of the above-ground corn plant dry matter (Shinners and Binversie, 2007). Stover roughly consists of 15% cob, 8% husk, 21% leaf, and 56% stalk by dry mass (Shinners and Binversie, 2007). 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, 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., 2007a, 2009, 2012; Webster et al., 2010). These systems involve size reduction of the stover on the combine harvester, with loose bulk collection in a towed container. This approach has three fundamental issues that hinder adoption: (1) combine productivity is reduced when stover collection rates are high; (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 the stover collection rate (Shinners et al., 2012). Depending on the type of size reduction and fraction of stover collected, bulk density in the collection container ranged from 40 to 100 kg DM 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, 2009; Glenvar, 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 m^{-3} (Webster et al., 2010) is greater than the reported density 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

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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 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 that utilizes a large-round baler (Keene, 2012). Its potential advantages compared to a towed large-square baler 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.

Figure 2. Schematic representation of material collecting in the accumulator hopper during bale wrapping and ejection.

Machine Description

A spout was added at the exit of the residue chopper of a John Deere model 9860STS combine (280 kW engine power) to facilitate collection of the stover leaving the harvester (figs. 1 and 2). 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, the crop is typically constrained by circumferentially wrapping the bale surface with twine or net mesh, a process that requires stopping the incoming crop stream to the bale chamber. Typically, this is accomplished by stopping the baler forward motion. When a round baler is applied to a single-pass grain and stover harvester, stopping the grain harvest to allow bale wrapping is deemed impractical. Therefore, components were added to a John Deere model 568 round baler to accumulate and hold stover during bale wrapping (figs. 1 and 2). 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 (i.e., the average difference from largest to smallest bale diameter was 3 cm or 1.9% of average bale diameter, n = 55).

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 h^{-1} using a 12-row corn header. A stover collection rate of 1.8 Mg DM ha^{-1} and bulk density of 50 kg DM 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 hydraulic power. The hydraulic power required by the accumulator conveyor and metering mechanisms was provided by auxiliary hydraulic outlets on the combine. Bales were typically wrapped with four layers of net mesh wrap.

Two types of corn headers (76 cm row spacing) were used: ear-snapper (ES) and whole-plant (WP). The ES header was a John Deere model 612C header (12 rows) with stalk-chopping rotors. The WP header was a John Deere model 666R header (six rows), 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

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.

the 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 were re-engaged. The hopper was then unloaded to about 80% empty (20% full), and the drives were again disengaged. This intermittent operation was referred to as the 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 1 kg 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 h (*ASABE Standards*, 2008a). 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 h (*ASABE Standards*, 2008b) 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 (HBM, Darmstadt, Germany) and pressure transducers located at the inlet and outlet of each motor. The theoretical torque required by each motor, ignoring losses, was calculated from the motor displacement and the pressure drop across the motor. The speeds of the baler drive and feed components were measured with magnetic speed pickups and 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 on which fuel use, engine speed, and ground speed packets were relayed. A Vector GL1000 compact logger (Vector Informatik, Stuttgart, Germany) was used to record the CAN bus packets, which were later decoded to engineering units using the SAE J1939 protocol (SAE, 2012).

Experiments Conducted

Although no formal experimental design was conducted, the stover collection rate relative to grain yield and the fraction of collected stover that was cob were 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 bale density settings were investigated by altering the cracking pressure of the relief valve that controls the tension of the baler belts. The high setting was maximum relief pressure, and the low setting was the valve opened two turns from maximum. Density data were analyzed using a one-way analysis of variance, treating each combination of field, header type, and baler density setting as a different treatment.

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 four replicates 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 using a fixed harvest distance of 176 m with each replicate test, the

Table 2. Experiments performed during the 2011 harvest season grouped by category.[a]

Experiment	Field	Harvest Dates	Table[b]
Feed system experiments:			
Hopper unload rate with ES stover	4	16-17 Nov.	5
Duty cycle with ES stover	1	26-28 Oct.	6
Hopper unload rate with WP stover	2	30-31 Nov.	7
Bale density:[c]			
Both ES and WP headers	1 to 4	Season	8
System fuel use experiments:			
Varied system configurations, WP	2	26-28 Oct.	9
Varied system configurations, ES	3	4-7, 18 Nov.	10

[a] Particulars concerning variety and crop conditions are found in table 1. WP = six-row whole-plant corn header, and ES = conventional 12-row ear-snapping corn header.
[b] Table in which the experiment results are shown.
[c] No formal bale density experiments were conducted; rather, density was compared using bales formed during other experiments throughout the harvest season.

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

Field	Variety[a]	Planting Date	Area Harvested (ha)	Grain Yield[b] ($Mg\ DM\ ha^{-1}$)	Harvest Dates	Grain Moisture (% w.b.)	Stover Moisture (% w.b.)
1	Dairyland 3105Q	9 May	11.9	7.0	12-19 Oct.	24	34
					23 Nov.	19	23
2[c]	Renk 670RR	28 April	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	4-7 Nov.	19	28
					18 Nov.	18	21
4	Pioneer P0448	5 May	5.3	-[d]	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 2 was harvested with the whole-plant corn header, so the stover moisture was greater due to greater stalk collection rate.
[d] No grain yield data were collected, as this field was used only for hopper unload tests.

hopper was filled to approximately the same volume for each treatment combination. With the WP header, a 2^2 randomized blocked design with four replicates 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.

The 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 re-engaged until the hopper was about 80% empty. The number of accumulator unloading events per bale and the time that 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 were used 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.

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., Cary, N.C.). For each analysis, a one-way ANOVA across all treatment combinations was performed, and least significant differences (LSD) between treatment means were calculated using Student t-test 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.

RESULTS

STOVER PROPERTIES

Header type and corn variety resulted in different stover collection rates and cob fractions (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 by 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 dry mass collected in single-pass bales to harvested grain dry mass across grain varieties and combine headers.[a]

Field	Corn Type	Header Type	Stover to Grain Harvested Mass Ratio: Mean[b]	SD
1	Silage	WP	0.61 a	0.05
1	Silage	ES	0.17 c	0.02
2	Grain	WP	0.47 b	0.05
3	Grain	ES	0.16 c	0.01

[a] Particulars concerning variety and crop conditions are found in table 1. WP = six-row whole-plant corn header, and ES = conventional 12-row ear-snapping corn header.
[b] Means followed by different letters are statistically different based on one-way ANOVA and Student t-test 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.[a]

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

[a] Particulars concerning variety and crop conditions are found in table 1. WP = six-row whole-plant corn header, and ES = conventional 12-row ear-snapping corn header.
[b] Least significant difference; values followed by different letters are statistically different ($\alpha = 0.05$).

ACCUMULATOR PERFORMANCE

The time required 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 required 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 fraction 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/retracted, high/retracted, low/engaged, and high/engaged, respectively. Stalk particle length was found to be linearly related to accumulator unloading time (fig. 3). Mass flow from the accumulator ranged from 12.0 to 22.5 Mg h^{-1} with an average of 16.7 Mg h^{-1}. At these unloading rates, operation of the accumulator could be intermittent because overall stover mass flow from the combine with the ES header ranged from 7.8 to 8.0 Mg h^{-1} (see table 9).

The time required to unload material collected with the WP header was greater than that with the ES header (table 6). In addition, the mass flow rate from the

Table 5. Time required 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.

Combine Configuration			Hopper Unloading Time (s)		Unloading Rate[d]
Chopper Speed[a]	Chopper Knives[b]	Conveyor Speed[c]	To 80% Empty	To 100% Empty	(Mg DM h^{-1})
Low	Out	Low	24 a	44 a	12.0
High	Out	Low	22 ab	42 ab	12.5
Low	In	Low	21 abc	35 bc	14.8
High	In	Low	17 bcd	29 cd	17.8
Low	Out	High	21 abc	34 c	15.5
High	Out	High	16 cd	30 cd	17.5
Low	In	High	18 bcd	25 d	20.7
High	In	High	14 d	23 d	22.5
		LSD (α = 0.05)[e]	5	7	-
Low	-	-	21 a	35 a	15.7
High	-	-	17 b	31 a	17.6
		LSD (α = 0.05)[f]	2	4	-
-	Out	-	21 a	37 a	14.4
-	In	-	17 b	28 b	18.9
		LSD (α = 0.05)[f]	2	4	-
-	-	Low	21 a	37 a	14.3
-	-	High	17 b	28 b	19.0
		LSD (α = 0.05)[f]	2	4	-

[a] Combine residue chopper speed (low = 1600 rpm; high = 2500 rpm).
[b] Stationary knife position in combine residue chopper (out = knives completely retracted; in = knives fully engaged).
[c] Speed of unloading conveyor on baler accumulator; low = 350 rpm; high = 400 rpm).
[d] Average feed rate calculated using total unloading time and final bale mass after replicate tests. Since there was no replication, no statistical analysis could be performed.
[e] Least significant difference; values in the same column followed by different letters are statistically different.
[f] Data were analyzed using a multiple-way ANOVA and pooled by the given factor level for comparison.

Table 6. Time required to empty the hopper and stover mass flow rate to the baler after filling the hopper struck-level full using the six-row whole-plant corn header.

Combine Configuration		Hopper Unloading Time (s)		Mean Unloading Rate[c]
Chopper Speed[a]	Chopper Knives[b]	To 80% Empty	To 100% Empty	(Mg DM h^{-1})
Low	Out	55 a	87 a	3.0
High	Out	38 b	54 b	4.8
Low	In	28 c	37 bc	6.9
High	In	22 c	27 c	9.6
	LSD (α = 0.05)[d]	7	19	-
Low	-	42 a	62 a	4.9
High	-	30 b	40 b	7.2
	LSD (α = 0.05)[e]	5	13	-
-	Out	47 a	71 a	3.9
-	In	25 b	32 b	8.2
	LSD (α = 0.05)[e]	5	13	-

[a] Combine residue chopper speed (low = 1600 rpm; high = 2500 rpm).
[b] Stationary knife position in combine residue chopper (out = knives completely retracted; in = knives fully engaged).
[c] Average feed rate calculated using total unloading time and final bale mass after replicate tests. Since there was no replication, no statistical analysis could be performed.
[d] Least significant difference; values in the same column followed by different letters are statistically different.
[e] Data were analyzed using a multiple-way ANOVA and pooled by the given factor level for comparison.

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. Fully engaging the combine chopper knives 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 from the accumulator ranged from 3.0 to 9.6 Mg h^{-1} with an average of 6.1 Mg h^{-1}. At these unloading rates, even continuous operation of the accumulator could not keep up with the stover mass flow from the combine equipped with the WP header, which averaged 11.3 Mg h^{-1} (see table 10).

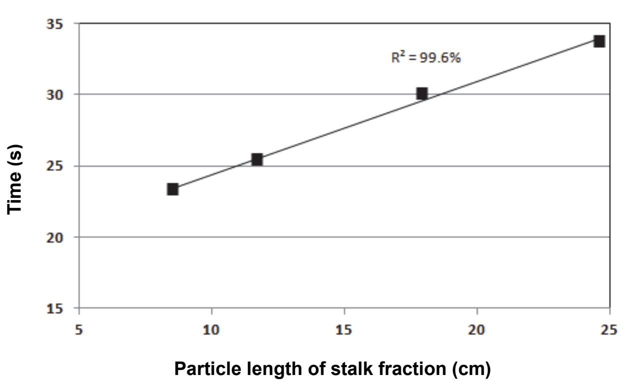

Figure 3. Time required to completely empty the accumulator hopper of stover harvested with the ES header as a function of geometric mean particle length of the stalk fraction (400 rpm conveyor speed).

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 the ES and WP headers, respectively. It was observed that small pieces of stover quickly 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.

Duty Cycle

When harvesting with the ES header, the accumulator metering system and baler were operated during just over one-third of the total time required to form a bale (table 7). An average of seven unloading events was required per bale, with an average event duration of 16 s. The average time that 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 the 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 (level

Table 7. Duty cycle summary for the accumulator metering system when harvesting stover collected with the ES header.

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

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

ground and cone index of 1240 kPa) was measured to be 5.5 and 11.6 kW at 4 and 8 km 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 the mass flow from the combine and the wrap cycle time (a 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, ensuring a nearly 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. 4). Bale density can be affected by grain present in the bales; however, hand-sorting bore samples showed that grain content was less than 0.5% by mass.

Table 8. Average bale density (dry basis) across all tests and settings.[a]

Field	Corn Type	Header Type	Baler Density Setting[b]	No. of Bales	Bale Density (kg DM m^{-3}) Mean[c]	SD
1	Silage	WP	Low	4	113 e	8
			High	-	-	-
1	Silage	ES	Low	16	122 d	7
			High	15	137 c	3
2	Grain	WP	Low	21	104 f	8
			High	12	120 de	8
4	Grain	ES	Low	-	-	-
			High	8	164 b	6
3	Grain	ES	Low	13	198 a	10
			High	4	206 a	8

[a] Particulars concerning variety and crop conditions are found in table 1. WP = six-row whole-plant corn header, and ES = conventional 12-row ear-snapping corn header.
[b] Baler density relief valve on John Deere 568 baler was fully tightened for the high level and loosened two turns for the low level.
[c] Means followed by different letters are statistically different based on one-way ANOVA and Student t-test confidence intervals at $\alpha = 0.05$.

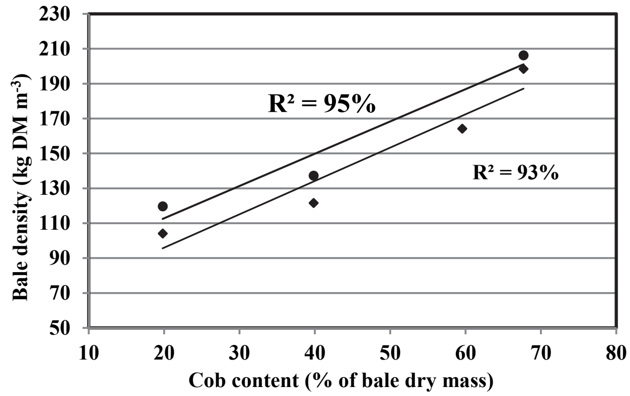

Figure 4. Average density of stover bales harvested with ES header as a function of cob content for high (●) and low (♦) density settings.

In general, large-square balers produce stover bales with greater densities than do large-round balers (Shinners et al., 2007b), yet the average density observed in field 3 was greater than the average density of 156 kg m^{-3} reported by Webster et al. (2010) for single-pass large-square bales. The density reported by Webster et al. (2010) was an average across the different stover collection rates achieved (1.6, 3.4, and 5.4 Mg 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 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 m^{-3}, which compares favorably with the values reported by Webster et al. (2010) for large-square bales.

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^{-1}, 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

Table 9. Harvest productivity and total combine fuel use when harvesting with the ES header using different combine chopper settings with and without the baler.

System Configuration[a]		Harvest	Stover Mass Flow	Specific Fuel Use	
Chopper Speed	Baler Use	Rate[b] (ha h^{-1})	Rate[c] (Mg DM h^{-1})	(L Mg^{-1} DM)[d]	(L ha^{-1})
Low	w/o baler	5.73 a	8.4 a	8.47 c	12.2 b
High	w/o baler	5.71 a	8.4 a	8.86 bc	12.8 ab
Low	w/ baler	5.62 b	7.8 a	9.36 ab	13.5 a
High	w/ baler	5.61 b	8.0 a	9.82 a	13.8 a
	-[e]	-	-	-	-
-	w/o baler	5.72 a	8.4 a	8.67 b	12.5 b
-	w/ baler	5.61 b	7.9 a	9.59 a	13.7 a
LSD (α = 0.05)[f]		0.11	0.6	0.46	1.5
Low	-	5.67 a	8.1 a	8.91 a	12.9 a
High	-	5.66 a	8.2 a	9.35 a	13.3 a
LSD (α = 0.05)[f]		0.11	0.8	0.44	0.7

[a] Four replicates were conducted with the baler, and two replicates were conducted without the baler. All bales were made at the low density setting over the distance required to make a full bale of 165 cm diameter. Chopper speed: low = 1600 rpm; high = 2500 rpm. Chopper knives fully engaged.

[b] Average harvest rate during bale formation; time required to wrap and eject the bales is not included. Harvest ground speed was adjusted to maintain target engine speed of 2250 rpm.

[c] Average harvested stover mass flow rate through the combine based on stover collected and harvest duration.

[d] Specific fuel use per stover dry mass; grain mass not included.

[e] Values in the same column followed by different letters are statistically different based on one-way ANOVA test and Student t-test confidence intervals at α = 0.05.

[f] Least significant difference; values in the same column followed by different letters are statistically different. Data were analyzed using multiple-way ANOVA and pooled by the given factor level for comparison.

Table 10. Harvest productivity and total combine fuel use when harvesting with the WP header using different combine chopper settings with and without the baler.

System Configuration[a]		Harvest	Stover Mass Flow	Specific Fuel Use	
Chopper Speed	Baler Use	Rate[b] (ha h^{-1})	Rate[c] (Mg DM h^{-1})	(L Mg^{-1} DM)[d]	(L ha^{-1})
Low	w/o baler	2.70 a	12.1 a	5.35 c	23.9 c
High	w/o baler	2.71 a	12.1 a	5.72 bc	25.5 bc
Low	w/ baler	2.50 b	11.3 a	6.02 ab	27.1 ab
High	w/ baler	2.54 b	11.3 a	6.43 a	28.4 a
LSD (α = 0.05)[e]		0.16	1.2	0.45	2.2
-	w/o baler	2.70 a	12.1 a	5.54 b	24.7 b
-	w/ baler	2.52 b	11.3 a	6.23 a	27.7 a
LSD (α = 0.05)[f]		0.11	0.8	0.30	1.5
Low	-	2.62 a	11.7 a	5.69 b	25.5 b
High	-	2.60 a	11.7 a	6.08 a	27.0 a
LSD (α = 0.05)[f]		0.11	0.8	0.30	1.4

[a] Four replicates were conducted for each combination of settings. All bales were made at the low density setting over a fixed harvest distance of 176 m. Average bale diameter of 173 cm. Chopper speed: low = 1600 rpm; high = 2500 rpm. Chopper knives fully engaged.

[b] Average harvest rate during bale formation; time required to wrap and eject bales is not included. Harvest ground speed was adjusted to maintain target engine speed of 2275 rpm.

[c] Average harvested stover mass flow rate through the combine based on stover collected and harvest duration.

[d] Specific fuel use per stover dry mass; grain mass not included.

[e] Least significant difference; values in the same column followed by different letters are statistically different.

[f] Data were analyzed using two-way ANOVA and then pooled to compare factor-level means.

productivity was reduced 2% and 56% when towing a round baler with stover collection rates of 1.4 and 4.5 Mg ha^{-1}.

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 in which material was collected during bale wrapping and ejection. The single-pass system achieved 5.6 ha h^{-1} while collecting stover yields of 1.4 Mg ha^{-1} with 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 that the combine had to supply power to operate the 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 baler 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.

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