INCREASING SINGLE-PASS CORN STOVER YIELD BY COMBINE HEADER MODIFICATIONS

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HIGHLIGHTS

- Rotary knives were added to an ear-snapper header to increase corn stover yield in a single-pass biomass system.
- Stover yield increased with the number of knives but at the expense of combine productivity and fuel consumption.
- Bale moisture was often greater than would be considered appropriate for good aerobic conservation.

ABSTRACT. *Modifications were made to a conventional ear-snapper corn header to increase corn stover yield when a single-pass round baling system was integrated with a combine harvester. To collect more leaves and top portions of stalks, knives oriented parallel to the deck plates were added to shear crop material above the ear-snapper rolls. Stover yield was primarily altered by the number of knives on the header; and to a lesser extent by the fore-and-aft position of the knives and the header height. The number of knives on a 12-row header was varied from two to six in increments of two. Stover yield increased linearly with the number of knives, and dry basis stover yield ranged from 1.1 Mg ha^{-1} (no knives) to 3.6 Mg ha^{-1} (six knives) over the five years of data collected (2012 to 2016). Combine productivity decreased linearly and specific fuel consumption increased linearly with greater stover yield. Combine productivity declined by as much as 50% when six knives were used. Dry basis bale density decreased linearly with the number of knives because the dense cobs became a smaller fraction of the total bale mass. In three of the five years, bale moisture increased linearly with the number of knives; in those three years, bale moisture was typically greater than 30% (wet basis). Adding knives to the header increased single-pass stover yield but at considerable cost to combine harvester productivity, and aerobic bale conservation would be challenged by high bale moisture.*

Keywords. *Baling, Combine, Corn, Density, Moisture, Productivity, Stover, Yield.*

Corn stover can be used as ruminant animal roughage feed, as animal bedding, or as a cellulosic feedstock for biofuels or bioproducts. The mass ratio of stover to grain is roughly 1:1 (Johnson et al., 2006; Shinners and Binversie, 2007), so greater stover yields have resulted from the genetic and agronomic practices that since 1955 have incrementally increased U.S. annual corn grain yield yield by 120 kg ha^{-1} (2 bu ac^{-1}) per year. While some corn residue needs to be retained to protect the soil from erosion and to sustain soil organic matter, removing excess residue has the potential to benefit subsequent crops. Benefits may include improved stand establishment and early plant growth, reduced nitrogen immobilization, and lower disease pressure (Robertson and Munkvold, 2007; Coulter and Nafziger, 2008). Managing the increasing quantity of corn residue, especially when continuous corn cropping is practiced, has increased the interest in harvesting a portion of the available corn stover.

The cost of stover harvest is impacted by the number of field operations required (Cook and Shinners, 2011). Single-pass systems in which stover harvest is combined with grain harvest have been investigated as a means to reduce costs and improve stover quality compared to conventional multi-pass systems (Webster et al., 2010, 2013). A single-pass round baler (SPRB) system integrated with a combine harvester has been commercialized (Hillco, 2016). Principal advantages of the SPRB system compared to conventional multi-pass stover harvest systems include fewer field operations, low soil contamination in the stover, greater yield of desirable stover fractions, and potentially lower cost.

When first introduced, the combine harvester with the SPRB system used an unmodified ear-snapper header that resulted in the harvest of mainly leaves, husk, and cobs (Keene et al., 2013). The harvest costs of this system were estimated to be greater than multi-pass systems because of the low stover yield associated with collecting only those fractions (Cook and Shinners, 2011). Increasing the single-pass yield by collecting more of the upper stalk reduced feedstock costs by 10% compared to multi-pass harvest systems (Cook and Shinners, 2011).

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When an ear-snapper header was used with a SPRB, the dry basis stover yield was 1.4 Mg ha^{-1} and the combine productivity was 5.6 ha h^{-1} (Keene et al., 2013). An alternative header that can attain much greater stover yield is a whole-plant header from a forage harvester. When the same combine harvester was equipped with this header, dry basis stover yields increased threefold to 4.5 Mg ha^{-1} but with a subsequent reduction in combine harvest rate to 2.5 ha h^{-1} (Keene et al., 2013). These results were similar to those of Webster et al. (2010) in which the area productivity of a single-pass system was highly dependent on the stover yield.

Varying the stover yield with a whole-plant header can be accomplished by altering the cut height. However, at grain harvest, most ears are no longer vertically upright but rather have rotated downward from the connection point on the stalk. Therefore, the header height must be set so that the cut-off knives are located below the tip of the lowest ears to prevent clipping the tips of the drooped ears with these knives. The cut height of a whole-plant header was limited to 63% of the ear connection point height to prevent clipping of the ear tips (Shinners et al., 2007). Whole-plant headers also have knives on every row, so there can be no row-by-row adjustments of the amount of stover collected because every row is cut at the same height. These two constraints determine the minimum attainable stover yield with a whole-plant header, and this yield may be greater than desired from the perspective of sustainability and combine performance. Finally, whole-plant headers from forage harvesters are not commonly owned by grain producers, and these headers are often not directly compatible with combine harvesters.

Despite the aforementioned advantages of single-pass systems, the low stover yields attained with conventional ear-snapper headers challenges the economics of this harvesting system. Corn header systems are needed that produce stover yields between the limits of those attained with unmodified whole-plant headers and ear-snapper headers. Therefore, the principal objective of this research was to modify a conventional ear-snapper header to provide greater corn stover yield when operated with a single-pass round baler system. Additional objectives were to quantify the performance of the combine harvester and the bale properties based on differences in stover yield resulting from the header modifications.

MACHINE DESCRIPTION

This research was conducted using a John Deere (Moline, Ill.) model 9860STS combine harvester and a John Deere model 612C 12-row chopping corn header. The corn stover that exited the rear of the combine was directed to a Hillco Technologies (Nezperce, Ida.) model JB510 SPRB system towed by the combine harvester (fig. 1). Incremental design modifications and improvements to the SPRB were made throughout this study, but the fundamental functional aspects of the machine remained consistent. During harvest, the accumulating hopper on the SPRB was filled from a spout located at the exit of the combine residue chopper (fig. 1). When the hopper was full, the baler drive was engaged, followed by the hopper unloading system. When the hopper was empty, both the unloading system and then the baler were stopped and the hopper began to fill again. This iterative process of filling and emptying was repeated until the desired bale diameter was reached. The hopper unloading system was then disengaged, the bale was wrapped with net wrap, and finally the bale was ejected to the ground. Typically, two to four iterative loading and unloading cycles were required to make a bale, depending on the stover yield and fractions collected. The process was automated and required no operator interaction other than initial inputs for bale diameter and number of layers of wrap.

The high-level design specifications of the project were: (1) modifications should be easily added or removed from the header, (2) no additional drive systems should be required, and (3) modifications should be able to be applied to any number of rows. To meet these specifications, rotating knives were mounted parallel to the deck plates just above the snapper rolls to cut the plants and capture a greater fraction of the leaves and upper stalks (fig. 2). The knives were 17 cm diameter, had 16 sharpened serrations, and were powered by the right-side gathering chain. Each knife cut the plants against a stationary anvil located just below the knife. The knife and anvil were integrated into the deck plate, so the three components could be removed as an assembly. No other modifications to the header (i.e., gathering chain length

Figure 1. Single-pass round baler (SPRB) collecting material exiting the combine harvester residue chopper during soybean harvest.

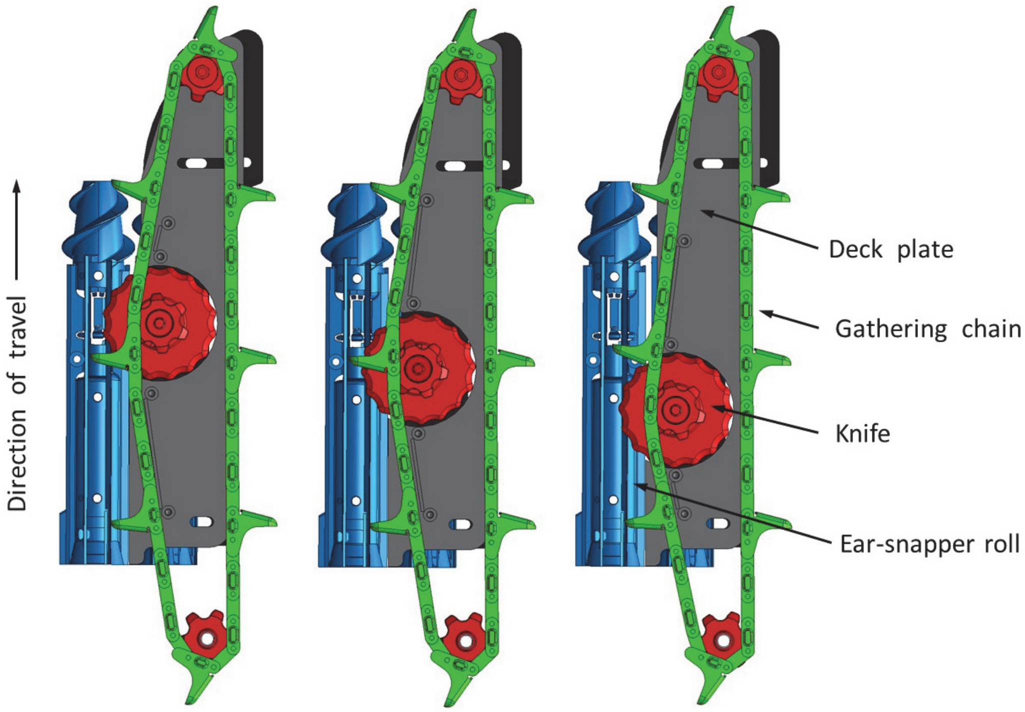

Figure 2. Modified ear-snapper row-units showing (left to right) forward, center, and rearward knives with knife centers located 36, 29, and 23 cm from the rear of the ear-snapper rolls. The left-side deck plates and gathering chains are not shown.

or additional components) were required. The change from conventional to modified deck plates required about 15 min per row using common hand tools.

It was hypothesized that stover yield would be increased by the greater forward position of the knives relative to the rear of the snapper rolls. Therefore, three different assemblies were fabricated with the knife center located 23, 29, and 36 cm from the rearmost part of the snapper roll (identified as rearward, center, and forward positions, respectively). The modified deck plates were always installed on the header in pairs.

MATERIALS AND METHODS

Combine performance was quantified by stover yield, stover mass flow rate, area productivity, and fuel consumption per unit area harvested. The combine header height was measured from the ground to the front of the ear-snapper rolls. In all years of this study, the header height was set at 40 cm, which was considered a typical harvest setting (table 1). In 2013 and 2014, an 80 cm height was used to reduce the harvested stover moisture content by leaving more of the wetter material behind because the bottom portion of the stalks had the greatest moisture content (Shinners and Binversie, 2007). The area harvested during a test was calculated by the width of the harvested strip (9.14 m) and the distance traveled to make one bale. The distance traveled was recorded to the nearest 0.3 m from the combine harvester's distance sensor. The duration of each test was measured with a stopwatch and recorded to the nearest second. The duration of each test encompassed the total time required to make a single bale. Stover mass flow rate was calculated from the dry mass of stover in one bale divided by the time required to make that bale. The grain harvested during each test was weighed using a grain cart equipped with load cells measuring to the nearest 5 kg. After each test, two representative grain samples were collected and then dried at 103°C for 72 h according to ASABE Standard S352.2 (ASABE, 2011a) for moisture determination.

Fuel use and engine speed were captured on the harvester's J1939 controller area network (CAN) bus with an ECOM (FW Murphy, Tulsa, Okla.) communication cable connected to the harvester's diagnostic CAN terminal. The signals sent over the CAN network were captured, decoded, and exported to an Excel spreadsheet according to the SAE J1939 protocol. During each test, ground speed was altered with the harvester's hydrostatic transmission so that the engine speed was maintained at approximately 2250 rpm in an attempt to maintain similar engine loading across all treatments.

Bales were 1.5 m wide and approximately 1.5 m diameter. Bale material properties were quantified by moisture content, dry basis density, and cob content as a fraction of the total dry bale mass. All bales were weighed on a platform scale with 1800 kg capacity and a resolution of 0.5 kg. The bale diameters were measured by hand to the nearest 2 cm on both sides of the bale in both the horizontal and vertical directions, and an average bale diameter was calculated. Each bale was subsampled twice with a boring tool of 10 cm diameter to collect samples used to determine moisture and cob content. The samples were taken on opposite corners of the bale and bored diagonally to a depth of approximately 80 cm. The samples were dried for 24 h at 103°C according to ASABE Standard S358.2 (ASABE, 2011b) to determine moisture content. After oven-drying, a particle separator, as described in ASABE Standard S424.1 (ASABE, 2011c), was used for separation of cob from the remaining material. After processing for 2 min, the cob was extracted by hand from each screen. The mass of the cob and non-cob fractions was determined to the nearest 0.1 g, and the cob fraction was calculated as a fraction of the total sample mass. Stover yield was calculated from the bale dry mass and the area harvested.

Experiments were conducted over a five-year period at the Arlington Agricultural Research Station (AARS) of the University of Wisconsin. In these tests, the number of header knives, header height, and position of the knives relative to the rear of the ear-snapper rolls was varied (table 1). Availability of different knife configurations, crop area available, stover moisture, and weather conditions prevented exact duplication of experimental conditions across every year of the study. Fields were laid out in plots, and experimental treatments were randomly assigned to the plots.

Full-factorial analysis using the Standard Least Squares option in the Fit Model platform of JMP Pro (ver. 13.1, SAS Institute Inc., Cary, N.C.) was used to conduct the statistical analysis on each year's data. Statistical differences of means were determined using either Tukey's test or Student's t-test both at 5% significance level.

RESULTS

The use of a greater number of knives significantly increased the dry basis stover yield in each year of the study (tables 2 to 5). Because an integer number of knives was used, stover yield was linearly related to the number of knives (fig. 3). When operated at 40 or 80 cm height, incremental stover yield increased by 31 and 16 percentage points, respectively, for each additional pair of knives used (fig. 3). Stover yield was reduced by an average of 16% when the header was raised from 40 to 80 cm (tables 3 and 4). Moving the knives forward by 7 cm (i.e., from center to forward position, fig. 2) increased stover yield by an average of 19% (tables 2 and 3). Stover mass flow rate through the combine was not significantly affected by the number of knives (tables 3 to 5) because the combine ground speed was reduced as stover yield increased to maintain a relatively constant engine speed.

Combine productivity was significantly reduced by processing additional stover when a greater number of knives was used (tables 2 to 5). Combine productivity decreased linearly with stover yield so that for every additional 0.5 Mg ha^{-1} of stover yield, combine productivity was reduced by 9 percentage points (fig. 4). Specific fuel consumption significantly increased with greater stover yield when more knives were used (tables 2 to 5). Specific fuel consumption

Table 1. Experimental conditions and details of experiments conducted in 2012 through 2016.

Year	Stalk Knives		Header Height[c] (cm)	Number of Replicates[d]	Harvest Dates	Grain	
	Number[a]	Position[b]				Dry Basis Yield (Mg ha^{-1})	Moisture Content (% w.b.)
2012	0, 2, 4	Forward or center	35	3	Oct. 21-22	8.51	17.9
2013	0, 2, 4, 6	Center	40 or 80	7	Oct. 21- 24	10.90	19.7
2014	0, 2, 4, 6	Center	40 or 80	7	Nov. 13-15	10.46	15.6
2015	0, 2, 4	Center	40	6	Dec. 4-7	10.43	18.8
2016	0, 2, 4, 6	Rearward	40	7	Nov. 5-6	9.66	20.1

[a] Number of rows on 12-row header that were equipped with stalk knives.

[b] Centers of knives were located 36, 29, and 23 cm from the rear of the ear-snapper rolls for the forward, center, and rearward positions, respectively.

[c] Header height was measured from the ground to the front of the ear-snapper rolls.

[d] Number of replicate bales created per experimental treatment.

Table 2. Harvester performance and bale properties for different numbers and positions of header knives in 2012.[a]

Number and Position of Knives[b]	Combine Harvester Performance								Bale Material Properties					
	Dry Basis Stover Yield (Mg ha^{-1})		Harvest Rate (ha h^{-1})		Stover Mass Flow Rate[c] (Mg h^{-1})		Specific Fuel Consumption (L ha^{-1})		Moisture Content (% w.b.)		Dry Basis Density (kg m^{-3})		Cob Mass Fraction[d] (%)	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
0	1.07 d	0.06	5.80 a	0.13	6.20 c	0.11	12.32 c	0.28	21.6 a	0.2	168 a	3	61 a	4
2 Center	1.33 c	0.03	5.26 b	0.03	7.02 abc	0.17	13.04 b	0.63	23.9 a	0.2	159 b	1	52 ab	6
2 Forward	1.55 b	0.09	5.31 b	0.01	8.23 ab	0.49	13.85 ab	0.33	21.3 a	0.8	161 ab	2	53 ab	3
4 Center	1.46 b	0.03	5.17 bc	0.32	7.56 abc	0.57	13.89 ab	0.61	21.4 a	0.5	156 b	1	43 b	4
4 Forward	1.89 a	0.11	4.77 c	0.10	9.05 a	0.73	15.29 a	0.21	23.6 a	0.7	156 b	2	43 b	7
Significance	<0.0001		0.0029		0.0281		0.0024		0.0062		0.0030		0.0049	
Averaged by knife position														
Center	1.40 b	0.04	5.22 a	0.15	7.29 b	0.29	13.46 a	0.43	22.7 a	0.6	158 a	1	47 a	4
Forward	1.72 a	0.10	5.04 a	0.13	8.64 a	0.44	14.57 a	0.37	22.5 a	0.7	158 a	2	48 a	4
Significance	0.0130		0.3826		0.0276		0.0805		0.8611		0.7420		0.9314	
Averaged by number of knives														
0	1.07 c	0.06	5.80 a	0.13	6.20 b	0.24	12.32 b	0.22	21.6 a	0.2	168 a	3	61 a	4
2	1.44 b	0.07	5.29 b	0.01	7.62 a	0.36	13.45 b	0.37	22.6 a	0.7	160 b	1	52 ab	3
4	1.68 a	0.11	4.96 b	0.17	8.31 a	0.53	14.59 a	0.42	22.5 a	0.6	156 b	1	43 b	3
Significance	<0.0001		0.0007		0.0014		0.0007		0.1353		0.0002		0.0236	

[a] Values are means and standard errors of the mean (SEM). Means in the same column followed by different letters differ using Tukey's test or Student's t-test at $p < 0.05$.

[b] Number of rows on 12-row header that were equipped with knives. Centers of knives were located 36 and 29 cm from the rear of the ear-snapper rolls for the forward and center positions, respectively. Header height was 40 cm as measured at the front of the ear-snapper rolls.

[c] Dry basis mass flow rate of stover through the combine harvester.

[d] Fraction of dry bale mass as cob.

Table 3. Harvester performance and bale properties for different numbers and positions of knives and different header heights in 2013.[a]

		Combine Harvester Performance								Bale Material Properties					
Number and Position of Knives[b]	Header Height[c] (cm)	Dry Basis Stover Yield (Mg ha^{-1})		Harvest Rate (ha h^{-1})		Stover Mass Flow Rate[d] (Mg h^{-1})		Specific Fuel Consumption (L ha^{-1})		Moisture Content (% w.b.)		Dry Basis Density (kg m^{-3})		Cob Mass Fraction[e] (%)	
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Without baler[f]	40			6.23	0.14			12.70	0.26						
	80			6.15	0.22			12.65	0.46						
0	40	1.67 b	0.15	4.72 ab	0.21	7.98 a	0.92	16.78 bcd	0.80	35.1 a	1.3	182 a	1	62 a	5
	80	1.37 b	0.27	5.67 a	0.26	7.91 a	1.89	13.15 d	0.19	32.1 ab	1.4	167 ab	3	64 a	4
2 Center	40	2.29 ab	0.20	3.94 c	0.08	8.99 a	0.79	18.34 bc	0.83	32.9 ab	1.5	175 ab	5	29 b	4
	80	1.90 b	0.39	4.26 bc	0.14	8.22 a	1.87	14.73 cd	0.49	26.7 ab	2.0	173 ab	6	37 b	4
4 Center	40	2.43 ab	0.22	3.44 cd	0.09	8.45 a	0.91	19.92 ab	0.86	33.2 ab	2.4	165 ab	4	28 b	5
	80	1.97 b	0.24	3.70 cd	0.47	7.18 a	1.01	17.05 bcd	1.99	26.5 ab	2.6	161 ab	5	39 b	3
6 Center	40	3.31 a	0.34	2.98 d	0.19	10.04 a	1.36	22.85 a	0.85	32.9 ab	2.5	164 ab	8	11 c	2
	80	2.43 ab	0.32	3.31 cd	0.15	8.18 a	1.40	20.12 abc	0.84	25.3 b	1.7	155 b	4	36 b	4
Significance		0.003		<0.0001		0.7902		<0.0001		0.0134		0.0154		<0.0001	
0	40	1.64 b	0.14	5.02 ab	0.20	8.24 a	0.81	16.01 cd	0.81	33.6 def	2.5	185 a	1	52 ab	4
	80	1.72 b	0.15	5.59 a	0.14	9.56 a	0.80	13.88 d	0.45	27.4 f	0.8	174 ab	2	68 a	2
2 Forward	40	2.24 b	0.16	4.44 bc	0.13	9.83 a	0.60	17.36 bcd	0.84	35.0 cde	1.5	171 ab	2	46 ab	3
	80	2.14 b	0.19	4.86 b	0.17	10.40 a	0.92	15.33 cd	0.62	28.8 ef	0.4	166 b	3	59 ab	4
4 Forward	40	2.85 ab	0.46	3.81 cd	0.13	10.73 a	1.66	19.42 bc	1.10	38.7 bcd	2.9	168 b	8	41 bc	9
	80	2.39 ab	0.25	3.82 cd	0.17	8.92 a	0.77	18.25 bcd	0.93	41.9 abc	0.8	146 c	2	43 b	6
6 Forward	40	3.92 a	0.66	2.77 e	0.16	10.42 a	1.31	25.20 a	1.83	46.6 a	1.5	148 c	1	17 c	1
	80	2.81 ab	0.45	3.26 de	0.15	9.04 a	1.29	21.43 ab	1.19	43.8 ab	0.5	144 c	1	41 bc	7
Significance		0.0012		<0.0001		0.7867		<0.0001		<0.0001		<0.0001		<0.0001	
Averaged by knife position															
Center		2.48 a	0.13	3.55 b	0.10	8.70 a	0.46	19.38 a	0.56	30.8 b	0.9	166 a	2	28 b	2.2
Forward		2.67 a	0.17	3.87 a	0.12	9.86 a	0.45	19.28 a	0.61	38.8 a	1.1	157 b	2	42 a	2.8
Significance		0.3984		<0.0459		0.0837		0.8805		<0.0001		0.0099		0.0002	
Averaged by header height															
	40	2.53 a	0.14	3.89 b	0.11	9.34 a	0.38	19.48 a	0.49	36.0 a	0.9	169 a	2	36 b	2.6
	80	2.09 b	0.12	4.30 a	0.15	8.97 a	0.40	16.74 b	0.54	31.6 b	1.1	161 b	2	48 a	2.5
Significance		0.0111		0.0422		0.5188		<0.0001		<0.0001		0.0002		<0.0001	
Averaged by number of knives															
0		1.60 c	0.08	5.25 a	0.12	8.42 a	0.47	14.96 c	0.45	32.1 b	1.0	176 a	1	62 a	2.2
2		2.14 bc	0.10	4.37 b	0.10	9.35 a	0.41	16.44 c	0.47	30.8 b	0.8	171 a	2	43 b	2.9
4		2.41 b	0.17	3.69 c	0.09	8.82 a	0.61	18.66 b	0.55	35.0 a	1.5	160 b	3	38 b	3.4
6		3.12 a	0.25	3.08 d	0.09	9.42 a	0.66	22.40 a	0.70	37.2 a	1.8	153 b	3	26 c	3.4
Significance		<0.0001		<0.0001		0.5315		<0.0001		<0.0001		<0.0001		<0.0001	

[a] Values are means and standard errors of the mean (SEM). Means in the same column followed by different letters differ using Tukey's test or Student's t-test at $p < 0.05$.

[b] Number of rows on 12-row header that were equipped with knives. Centers of the knives were located 36 and 29 cm from the rear of the ear-snapper rolls for the forward and center positions, respectively.

[c] Header height measured from the ground to the front of the ear-snapper rolls.

[d] Dry basis mass flow rate of stover through the combine harvester.

[e] Fraction of dry bale mass as cob.

[f] Combine harvester operated without single-pass round baler pulled behind the harvester and without header knives.

increased linearly with stover yield so that for every additional 0.5 Mg ha^{-1} of stover yield, fuel use increased by 17 percentage points (fig. 5). Productivity decreased and fuel use increased because of the greater effort required to process the greater mass of stover through the harvester's threshing, separation, and residue chopping components and because the baler system operated more frequently with greater stover yield. The comparison baseline for combine productivity and fuel use was with the combine equipped with the SPRB and no header knives. The impact on combine productivity and fuel use was greater when the comparison combine configuration was the harvester alone without the SPRB or header knives (table 3). In this comparison, productivity was reduced by 15% to 50% depending on the number of knives and the header height.

In 2012 through 2016, there were few statistical differences in bale moisture as affected by the number and position of the knives (tables 2 to 5). When the stover moisture was greater than 30% (w.b.), there was a trend for bale moisture to increase linearly ($R^2 = 0.91$ to 0.99) with the addition of knives. Stalks hold more water than other plant parts as autumn progresses, but the top of the stalks and the leaves are typically drier than other plant parts (Shinners and Binversie, 2007), and these were the primary additional fractions captured when using the header knives. However, in three of the five years of this study, the average moisture across all treatments was greater than 30% (w.b.), which would raise concerns about biological degradation of the bales. This was the case for most bales formed in 2013 and 2015, as they were observed to notably heat and lose shape shortly after formation. Knife position did not significantly affect stover moisture in 2012 when the stover was relatively dry (table 2); however, in 2013, the stover moisture was less when the knives were positioned rearward (table 3).

Previous research showed that single-pass stover bale density was correlated with cob mass fraction (Keene et al., 2013), and this relationship was also found here. Within each experiment shown in tables 2 through 5, the bale density was linearly correlated with cob mass fraction ($R^2 = 0.86$ to 0.99). Each incremental addition of two header knives diluted the cob mass fraction of the bale by approximately 15 percentage points and reduced the bale density by approximately 5 percentage points. Grain moisture varied across years (table 1), and stover moisture increased with grain moisture (fig. 6).

Table 4. Harvester performance and bale properties for different numbers of header knives and header heights in 2014.[a]

		Combine Harvester Performance								Bale Material Properties					
Number and Position of Knives[b]	Header Height[c] (cm)	Dry Basis Stover Yield (Mg ha^{-1})		Harvest Rate (ha h^{-1})		Stover Mass Flow Rate[d] (Mg h^{-1})		Specific Fuel Consumption (L ha^{-1})		Moisture Content (% w.b.)		Dry Basis Density (kg m^{-3})		Cob Mass Fraction[e] (%)	
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
0	40	1.95 c	0.16	5.38 ab	0.27	10.48 a	0.94	14.56 cd	0.65	25.5 a	0.3	181 ab	2	72 a	3.4
	80	1.90 c	0.07	5.86 a	0.29	11.06 a	0.16	13.24 d	0.59	25.4 a	0.2	186 a	2	72 a	3.1
2 Center	40	2.44 bc	0.12	4.52 cd	0.09	11.04 a	0.67	17.17 bc	0.35	25.8 a	0.8	158 d	2	60 abc	3.9
	80	2.17 bc	0.15	4.92 bc	0.23	10.65 a	0.80	16.01 cd	0.77	24.9 a	1.0	173 bc	2	65 ab	4.2
4 Center	40	3.07 ab	0.24	3.89 de	0.11	11.94 a	1.00	19.90 ab	0.57	26.0 a	0.7	148 e	2	43 bc	2.2
	80	2.52 bc	0.30	4.45 cd	0.08	11.18 a	1.30	17.28 bc	0.25	25.9 a	0.6	161 d	2	52 abc	5.6
6 Center	40	3.53 a	0.29	3.49 e	0.11	12.21 a	0.77	20.45 a	1.13	21.0 b	0.6	155 de	3	42 c	4.3
	80	2.61 abc	0.13	4.77 bc	0.06	12.48 a	0.73	15.39 cd	0.47	20.5 b	0.5	164 cd	3	56 abc	4.0
Significance		<0.0001		<0.0001		0.6881		<0.0001		<0.0001		<0.0001		0.0007	
Averaged by header height															
	40	2.73 a	0.16	4.32 b	0.18	11.64 a	0.40	17.69 a	0.66	24.6 a	0.6	162 b	3	54 a	3.7
	80	2.31 b	0.11	4.88 a	0.11	11.28 a	0.47	15.81 b	0.34	24.2 a	0.6	170 a	2	61 a	3.1
Significance		0.0102		0.0045		0.5861		<0.0001		0.4895		<0.0001		0.0604	
Averaged by number of knives															
0		1.92 c	0.10	5.62 a	0.21	10.77 a	0.57	13.90 c	0.50	25.9 a	0.2	184 a	2	72 a	2.3
2 Center		2.31 bc	0.10	4.72 b	0.13	10.84 a	0.50	16.59 b	0.44	25.5 a	0.6	165 b	3	63 a	3.4
4 Center		2.79 ab	0.20	4.18 c	0.11	11.56 a	0.79	18.60 a	0.50	25.3 a	0.4	154 c	2	49 b	3.9
6 Center		3.07 a	0.20	4.13 c	0.20	12.35 a	0.51	17.92 ab	0.96	20.8 b	0.4	160 bc	2	48 b	4.1
Significance		<0.0001		<0.0001		0.2933		0.0005		<0.0001		<0.0001		0.0001	

[a] Values are means and standard errors of the mean (SEM). Means in the same column followed by different letters differ using Tukey's test or Student's t-test at $p < 0.05$.

[b] Number of rows on 12-row header that were equipped with knives. Centers of knives were located 29 cm from the rear of the ear-snapper rolls for the center position.

[c] Header height was measured from the ground to the front of the ear-snapper rolls.

[d] Dry basis mass flow rate of stover through the combine harvester.

[e] Fraction of dry bale mass as cob.

DISCUSSION AND CONCLUSIONS

Modifying an ear-snapper corn head with rotary knives located on the deck plates achieved the objective of increasing the dry basis stover yield, specifically by 31 percentage points for each additional pair of knives used. Stover yield was most affected by the number of knives used, and to a lesser extent by the header height and knife position. The knife assemblies were intended to be easily added or removed to allow producers to manage stover yield by altering the number of rows with knives. Ground speed was altered to maintain a constant engine speed to achieve similar engine loading across all treatments. As stover yield increased, the combine ground speed had to be reduced to maintain engine speed, so productivity decreased and fuel consumption per unit area increased. Had it been possible to maintain a relatively constant ground speed across all treatments, the impact on productivity would have been negligible. However, engine power would likely have become limited, and the danger of plugging the combine would certainly have increased. Combine harvesters with more powerful engines and internal components that can process more material other than grain (MOG) would likely be required to maintain combine productivity as stover yield is increased with this header modification.

A comparison of knife positions was investigated in two years of this study (table 1), primarily to determine the impact on stover yield and moisture. Operating the knives in the forward position increased stover yield (tables 2 and 3). Moving the knives 7 cm forward produced approximately the same increase in yield as the addition of one knife. Stover moisture was not significantly different based on knife position when the stover was relatively dry (table 2). In 2013, moving the knives 7 cm rearward reduced stover moisture (table 3), but the moisture was still greater than what would be considered acceptable for safe aerobic conservation.

An elevated header height of 80 cm was investigated in two years of this study (table 1), primarily as a means to reduce stover moisture. Stover moisture was statistically less

Table 5. Harvester performance and bale properties for different numbers and positions of header knives in 2015 and 2016.[a]

	Combine Harvester Performance								Bale Material Properties					
Number and Position of Knives[b]	Dry Basis Stover Yield (Mg ha^{-1})		Harvest Rate (ha h^{-1})		Stover Mass Flow Rate[c] (Mg h^{-1})		Specific Fuel Consumption (L ha^{-1})		Moisture Content (% w.b.)		Dry Basis Density (kg m^{-3})		Cob Mass Fraction[d] (%)	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
2015														
0	1.87 c	0.08	4.12 a	0.1	7.71 a	0.26	16.84 b	0.25	30.3 a	2.2	160 a	5	63 a	1
2 Center	2.45 b	0.08	3.61 b	0.1	8.84 b	0.29	20.13 b	0.31	33.1 a	0.5	150 ab	3	58 b	2
4 Center	2.87 a	0.09	3.64 b	0.1	10.45 c	0.27	20.12 b	0.29	34.9 a	1.5	142 b	1	53 c	1
Significance	<0.0001		0.0003		0. 0002		<0.0001		0.1652		0.0175		0.0052	
2016														
0	2.08 b	0.20	3.74 a	0.09	7.76 a	0.40	17.24 b	0.29	29.0 b	0.7	169 a	1	67 a	4
2 Rearward	2.11 b	0.10	4.03 a	0.34	8.40 a	0.59	17.19 b	1.07	29.4 b	0.5	158 b	2	49 b	4
4 Rearward	3.01 a	0.25	3.40 a	0.13	10.31 a	1.09	20.66 b	0.73	30.2 b	0.5	146 c	1	40 bc	3
6 Rearward	3.54 a	0.25	2.52 b	0.23	8.82 a	0.69	25.66 a	1.38	32.5 a	0.5	137 d	1	33 c	2
Significance	<0.0001		0.0001		0.1750		<0.0001		0.0009		<0.0001		<0.0001	

[a] Values are means and standard errors of the mean (SEM). Means in the same column followed by different letters differ using Tukey's test or Student's t-test at $p < 0.05$.

[b] Number of rows on 12-row header that were equipped with knives. Centers of knives were located 29 and 24 cm from the rear of the ear-snapper rolls for the center and rearward positions, respectively. Header height was 40 cm as measured at the front of the ear-snapper rolls.

[c] Dry basis mass flow rate of stover through the combine harvester.

[d] Fraction of dry bale mass as cob.

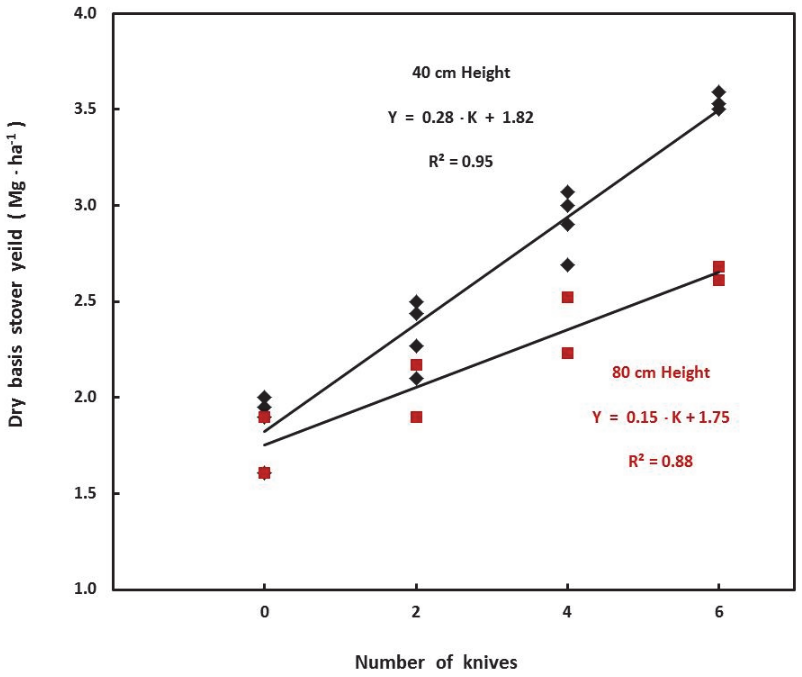

Figure 3. Number of knives (K) versus dry basis stover yield (Y) for data collected in 2013 through 2016 (40 cm header height) and in 2013 and 2014 (80 cm header height). Header height measured from the ground to front of ear-snapper rolls.

in 2013 with the 80 cm header height (table 3), but the moisture was still greater than what would be considered acceptable for safe aerobic conservation. When the stover was drier in 2014 (table 4), operating at 80 cm did not statistically reduce stover moisture. In both 2013 and 2104, operating at the elevated header position significantly reduced stover yield, increased area productivity, and reduced specific fuel consumption (tables 3 and 4) compared to operating at 40 cm height. However, if the crop is short, down, or lodged, then operating at the elevated height of 80 cm would not be practical.

Grain loss is known to increase with the MOG feed rate, although this relationship is stronger for crops where the MOG feed rate is high (i.e., small grains) compared to corn where the MOG feed rate is relatively less (Isaac et al., 2006). Previous to this research, both an ear-snapper and a whole-plant header were used to harvest single-pass stover collected in a wagon pulled behind the combine (Shinners

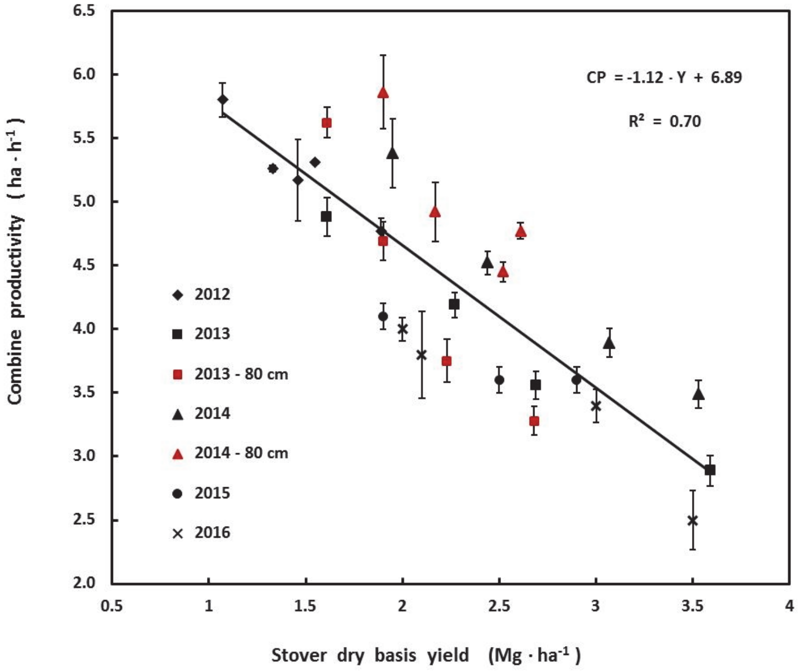

Figure 4. Dry basis stover yield (Y) versus combine productivity (CP) for data collected when combine header operated at 40 cm height, except where noted. Error bars represent standard errors of the mean.

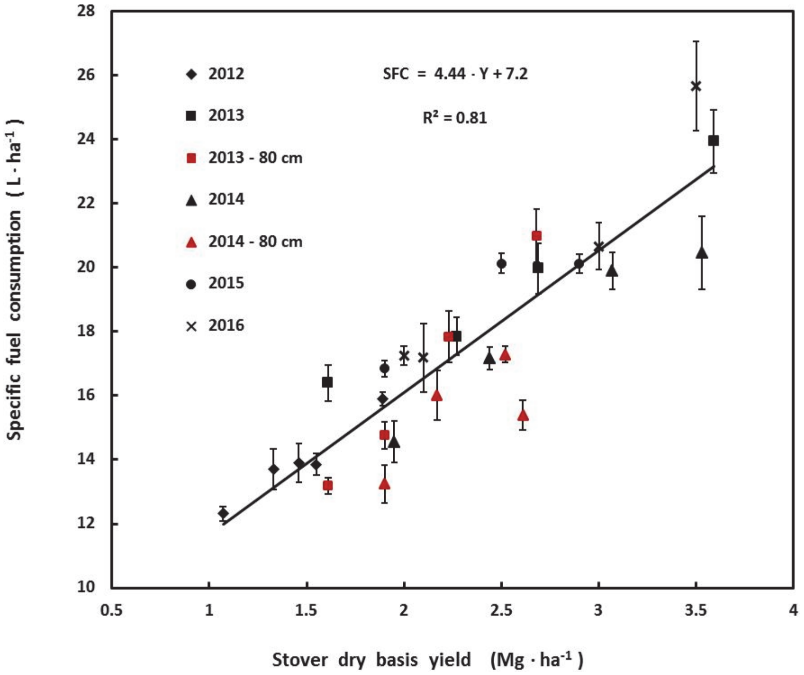

Figure 5. Dry basis stover yield (Y) versus combine specific fuel consumption (SFC) for data collected when combine header operated at 40 cm height, except where noted. Error bars represent standard errors of the mean.

et al., 2007). Although the MOG feed rate was 67% greater when the whole-plant header was used, the material in the wagon had grain content similar to when the ear-snapper header was used. In earlier SPRB research, the grain content in the bale was less than 0.5% by mass (Keene et al., 2013). Although the grain content in the bales was not quantified in this study, it is possible that grain loss to the bales would have been relatively unaffected by the use of header knives because the MOG feed rate was typically statistically similar across treatments. Clipping the tips of the ears by the knives was not observed, and there were no observed differences across treatments in header grain loss to the ground.

Depending on intended use, corn stover anatomical fractions have variable properties that make some fractions more desirable than others. For instance, the leaf and husk had greater ruminant digestibility, as measured by *in vitro* dry matter disappearance (IVDMD), than the stalk and cob (Fernandez-Rivera and Klopfenstein, 1989). The top portion of

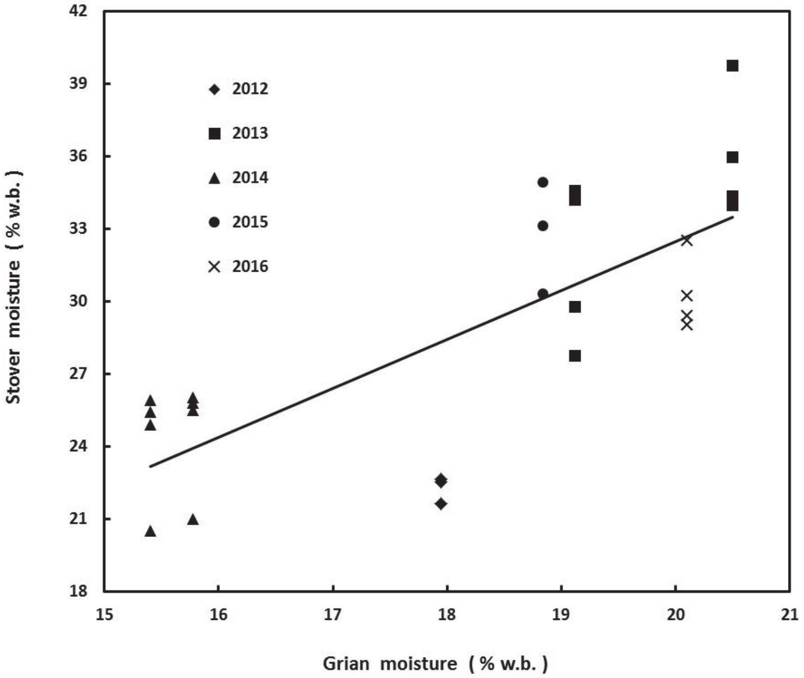

Figure 6. Grain moisture versus stover bale moisture for data from 2012 through 2016. Data include all header knives and header heights considered ($R^2 = 0.56$).

the stalk had greater IVDMD than the bottom portion, which tends to have more lignin (Watson et al., 2015). Gutierrez-Ornelas and Klopfenstein (1991) reported that cattle selectively consumed husks and leaves before other plant parts. Cob made up most of the refusals from beef cattle fed single-pass corn stover (Updike et al., 2015). It was observed that the additional stover collected by the header knives consisted mainly of leaves and the top portion of stalks, two fractions that have better digestibility than the bottom portion of stalks that typically make up the greatest fraction of conventional baled stover. Single-pass corn stover bales had greater starch content than conventional stover bales, likely because grain that normally would have been lost from the rear of the combine was collected in the baler (Hillco, 2019). Steers consuming single-pass stover with anatomical fractions similar to the no-knife treatment studied here had greater average daily gain, DM intake, and feed:gain ratio compared to steers that were fed conventional stover that was dominated by stalks (Updike et al., 2015). Additional research is needed to determine how changes in the anatomical fractions collected by the use of header knives might impact ruminant animal performance.

Changes to the composition of single-pass bales could also have a positive impact on biomass intended for biochemical conversion to ethanol. Duguid et al. (2009) showed that the lower portion of the stalk was the most recalcitrant fraction, with only half of the available glucan being hydrolyzed in dilute alkaline pretreatment and enzymatic hydrolysis compared to the cob, husk, and leaf fractions. The same study also reported that the top portion of the stalk had similar projected ethanol conversion as the leaf, husk, and cob fractions. The xylan, galactan, and arabinan contents tended to increase from bottom to top of the stalk, and the estimated ethanol yield per unit mass was significantly greater for the top half of the stalk than the bottom half (Shinners et al., 2007). Because the use of header knives collects more of the leaves and upper stalks, it is possible that ethanol yield could be greater compared to conventional stover, which is dominated by the more recalcitrant lower stalks.

Bale density was reduced when more knives were used, and this could negatively impact feedstock logistics costs. The dry basis density of stover bales harvested using conventional multi-pass methods ranged from approximately 110 to 130 kg m^{-3}, from 110 to 150 kg m^{-3}, and from 140 to 210 kg m^{-3} for bales formed with round balers, conventional large square balers, and high-density large square balers, respectively (Prewitt et al., 2007; Shinners and Friede, 2018). When six header knives were used, dry basis bale density ranged from approximately 150 to 165 kg m^{-3}, which was similar to that achieved with multi-pass stover in conventional large square bales.

Ash consists of minerals naturally occurring in the growing plant (endogenous) and exogenous minerals that are primarily associated with soil contamination during harvest. Exogenous ash in beef or dairy cattle rations is undesirable because it provides no nutritional value while taking up rumen space that could be occupied with digestible nutrients (Hoffman, 2005; Bannink et al., 2016). From a bioenergy perspective, ash content is of particular concern because of slagging, fouling, and corrosion in thermochemical processes, displacement of fermentable carbohydrates, and displacement of potential buffering capacity during pretreatment in biochemical conversion (Bonner et al., 2014). Ash contents with conventional baled stover systems ranged from 12% to 28% of DM (Bonner et al., 2014), while ash contents of single-pass stover ranged from 4% to 6% (Hoskinson et al., 2007; Shinners et al., 2012; Cook et al., 2014). Because the stover collected with the system investigated here never contacted the ground, it can be inferred that the addition of header knives to increase yield would produce stover with ash contents similar to other single-pass systems that collected similar anatomical fractions.

The moisture content of single-pass stover is a major hurdle to its successful application as a harvesting system. Post-grain harvest practices such as shredding, tedding, and raking that are typically used to enhance stover drying and reduce stover bale moisture cannot be used with the single-pass method. Previous research has shown that the moisture of single-pass stover was often well above what would be considered acceptable for aerobic conservation in bales (Hoskinson et al., 2007; Shinners et al., 2011; Updike et al., 2015). It was hypothesized that the header knives would collect the top potion of the plants that was known to have lower moisture than the bottom stalks (Shinners and Binversie, 2007), so the aggregate moisture of the stover might have been within the acceptable range for safe aerobic conservation. However, the average bale moisture was greater than 30% (w.b.) in three of the five years of this study, and employing more header knives tended to increase the stover moisture. Even when grain moisture was less than 16% (w.b.), aggregate bale moisture was greater than 25% (w.b.) (fig. 6). Genotype, planting dates, and weather during the growing season had little influence on grain post-maturity drying rate, but these factors significantly influenced grain moisture content at physiological maturity (Martinez-Feria et al., 2019). Temperature, relative humidity, and vapor pressure deficit are the primary variables that impact grain drydown rate after physiological maturity. Algorithms developed by Martinez-Feria et al. (2019) show that grain moisture will not be less than 16% (w.b.) until late October for much of the Corn Belt. Based on the relationship between grain moisture and single-pass bale moisture (fig. 6), single-pass stover may have greater moisture than desired for safe aerobic conservation during much of the harvest season in the Corn Belt.

The addition of header knives increased the yield of single-pass stover, and the stover yield was easily modified by the number of knives used. However, combine productivity and specific fuel consumption were affected by these header modifications. The moisture content of the collected material was often well above that considered acceptable for aerobic conservation. For these header modifications to be widely adopted, combines with more powerful engines and greater MOG processing ability may be required to maintain productivity close to current expectations. Bales will likely have to be economically wrapped in plastic film and conserved through anaerobic fermentation to achieve a robust single-pass combine-baler system that can be employed independent of standing crop moisture.

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