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Comparison of wet and dry corn stover harvest and storage

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Abstract

Corn stover has great potential as a biomass feedstock, but harvest and storage of this material is challenged by weather conditions at harvest; material moisture; and equipment shortcomings. Field drying characteristics, harvest efficiency and rate, product bulk density, and storage characteristics were quantified for stover harvested and stored in wet or dry form. Only in one case did stover reach dry baling moisture (~20%) in the first 4 d of field drying. Conventional hay and forage harvesting equipment (shredder, rake, forage harvester, round baler, and square baler) produced an average harvested yield of about 30% of the total available stover mass. Harvesting capacity of this equipment was limited by difficulty in gathering shredded stover. The density of chopped or baled stover was less than that typically expected with hay and forage crops. Losses of wet stover ensiled at 44% moisture averaged 3.9% with low levels of fermentation products. Dry stover losses were 3.3% and 18.1% for bales stored indoors and outdoors, respectively. Harvesting wet stover right after grain harvest was timelier and resulted in a greater harvesting rate and yield compared to dry stover harvest. Storing wet stover by ensiling resulted in lower losses and more uniform product moisture compared to dry stover bales stored outdoors.

Keywords: Biomass; Corn stover; Ensiling; Bales; Harvest; Storage; Maize; Dry matter losses

1. Introduction

Corn stover is the nongrain portion of the corn plant and consists of the stalk, leaf, cob and husk fractions. Corn stover has the greatest potential as a biomass feedstock in North America, with potential annual yields of 130 Tg producing 38.4 GL of bioethanol [1]. Compared to other biomass commodities such as switchgrass, hybrid poplars and small-grain straw, corn stover has considerable advantages in that the grain fraction is a high value co-product, and the yield of corn stover is quite high. Among many possible uses, corn stover has been proposed as a feedstock for enzymatic hydrolysis of cellulose to fermentable sugars to produce fuel ethanol, direct combustion or gasification to produce electricity, and processing of specific fractions into a supplemental fiber source for paper pulp.

Corn stover has been harvested as supplemental feed for beef and nonlactating dairy animals for decades. Typically it is harvested as a dry product (~20–25% moisture) packaged in dense round bales or loose stacks, with both stored outdoors. Harvesting as a dry product typically involves using available hay harvesting equipment. The stover is first harvested with a flail shredder, then field dried, gathered with a rake, and finally baled with a large round baler. Shredding and windrowing can be combined, but this can slow drying during an already difficult drying period, so most producers shred and lay the stover as wide as possible to facilitate drying. The time after grain harvest for stover to reach baling moisture has been reported to take from several days to weeks because of the low ambient temperatures and frequency of rain during the fall harvest season [2]. Richey et al. [3] reported that less than two-thirds of available stover was collected by the shredder and of that only 50% was collected by a large round baler, yielding a harvesting efficiency of about 30%. They also reported that DM losses in round bales stored outdoors ranged from 10 to 23% depending on initial stover moisture.

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Nomenclature

ADF	acid detergent fiber
DM	dry matter
LRB	large round baler
LSB	large square baler
LSD	least square difference
NDF	neutral detergent fiber
P	probability
TLC	theoretical length-of-cut
WM	wet matter

Stover is sometimes harvested wet (>45% moisture) and preserved by ensiling [4–6]. This harvest and storage method eliminates the need for field drying, and greatly improving timeliness. Fermentation can also improve the palatability of the feed. When harvesting as a wet product, the shredder typically follows right behind the combine harvester, shredding and windrowing in a single pass. A forage harvester with windrow pickup is used to gather and size-reduce the stover prior to ensiling. Several researchers have reported that successful preservation of corn stover was dependent upon initial stover moisture and ability to achieve an anaerobic environment in storage [4–7]. However, harvesting productivity, fraction of crop harvested, initial moisture and storage DM losses were not well quantified in these studies.

If corn stover is to become a widely harvested and marketable commodity, significant improvements in harvest and storage systems are required. Because corn stover availability typically greatly exceeds on-farm demand as a supplemental animal feed, there has not been much economic incentive to improve stover harvesting systems. The first step in improving these systems is to quantify the performance of current systems which use conventional hay and forage harvesting equipment. Therefore, the specific objectives of this research were to determine the drying rate of corn stover after grain harvest as affected by harvest date and conditioning treatment, to compare the field performance of conventional hay and forage harvesting equipment used to harvest wet or dry stover and to determine the storage characteristics of wet and dry stover.

2. Materials and methods

All tests were conducted at the University of Wisconsin Arlington Agricultural Research Station (AARS) located at 43.326868N, 89.363082W. Grain hybrids with comparative relative maturity recommended for south-central Wisconsin (~105 d) [8] were chosen for study in 2002 and 2003.

2.1. Stover drying characteristics after grain harvest

Four drying trials were conducted, beginning on 10/9/02, 10/21/02, 10/2/03, and 10/10/03. Within a few hours of grain harvest, a portion of a field was subdivided into four replicated blocks (each ~100 m long) and these treatments randomly assigned and applied within each block: untreated; shredded and placed in a wide swath (~4.5 m wide); and shredded and placed in narrow windrow (~1 m wide). In 2003, a fourth treatment was added consisting of a shredded and doubled windrow (i.e. two single windrows merged into one at shredding). In 2002, shredding was accomplished with a 4.6 m wide Buffalo[1] model 4915 flail shredder equipped with windrow forming shields. In 2003, shredding was accomplished with a 4.6 m wide Balzer[1] model 1500 flail shredder which could not form a windrow. Therefore, a single or double rotary rake was used to form the single or double windrows, respectively. In both years, the shredder was operated 10 cm above the soil surface at a forward speed of 6.5 km h^{-1}.

Samples for moisture determination were collected the day of grain harvest and daily for 3 d after that if weather permitted. Samples were collected sporadically after that as weather permitted, but typically samples were collected every 2 or 3 d for up to 20 d after grain harvest. At each collection time, one sample was collected from each subplot in all 4 blocks by hand gathering all the material in an area about 0.5 m^2 that spanned across 2 rows. Samples were placed in plastic bags, transported to a laboratory, sized reduced in a laboratory chopper, and the entire subsample oven dried at 103 °C for 24 h [9]. The 4 replicate moisture samples were then pooled and plotted versus time.

2.2. Chopped stover

One field was harvested on 10/09/02 and one field each harvested on 10/13/03 and 10/30/03. Within several hours of grain harvesting, the stover was shredded and windrowed using a 6 m wide Hiniker[1] model 5600 flail shredder set at 15 cm height (Table 1). The shredder formed a windrow on the far right-hand side of the machine and another windrow was placed immediately adjacent to the first on the subsequent pass in the opposite direction in order to double the windrow size to match the capacity of the forage harvester. A John Deere[1] model 6950 self-propelled forage harvester equipped with a 4.5 m wide model 645 windrow pickup was used to gather and chop the stover. The harvested material was collected in a side-dumping forage wagon equipped with load cells to determine harvested mass. The material was dumped into trucks, and the volume occupied by the stover quantified to calculate chopped stover density. The forage harvester was

[1]Mention of trade names in this manuscript are made solely to provide specific information and do not imply endorsement of the product or service by the University of Wisconsin-Madison and the USDA–ARS.

Table 1
Chronological order of field operations performed after grain harvest for the three harvesting scenarios studied

Order of operation	Stover harvesting scenarios		
	Chopped	Baled—wet	Baled—dry
1	Shred/merge[a]	Shred	Shred
2	Wilt	Rake	Dry
3	Chop	Wilt	Rake
4	Transport	Bale	Bale
5	Bag	Gather	Gather
6		Transport	Transport
7		Wrap/store[b]	Store

[a]Shredding and merging accomplished with one machine.
[b]Wrapping and storing accomplished in one step.

used to harvest 15 loads/field, 5 each at 6.4, 12.7 and 19.1 mm theoretical-length-of-cut (TLC). The time and distance required to harvest a load was also quantified so that harvesting rate and yield could be determined. The material was then stored in 3.0 m diameter plastic silo bags and the length and diameter of the silo bag at each load determined so that silo density could be calculated. Moisture was determined on 3 sub-samples/load by oven drying at 103 °C for 24 h [9]. Particle size by screening was determined on 3 sub-samples/TLC [9]. Particle size was also determined on 2 or 3 sub-samples of both the untreated and shredded stover prior to chopping.

The silo bag made in 2002 was opened on 7/8/03 and the silo bags made in 2003 were both opened on 7/23/04. The stover was removed with a wheel loader and spillage was hand collected to minimize takeout losses. The removed stover was weighed on a truck scale accurate to the nearest 2.3 kg. Three sub-samples were taken at each original load location in the bag and oven dried at 60 °C for 72 h [9] so that volatiles formed from fermentation during the ensiling process were not driven off.

Eight additional random samples removed from each silo bag were oven dried at 60 °C, hammer milled to 1 mm particle size and then analyzed for ash content, nitrogen, acid-detergent fiber (ADF), and neutral-detergent fiber (NDF) using wet laboratory analysis techniques. Another eight random samples were also taken from each silo bag, frozen and then sent to Dairyland Laboratories (Arcadia, WI) for analysis of pH and fermentation products (lactic acid, acetic acid, butyric acid, and ethanol) through the use of high performance liquid chromatography.

2.3. Baled stover—wet product

Grain harvesting and wet stover baling took place on 10/11/02, 10/24/03 and 10/30/03. Within an hour of grain harvesting the stover was shredded using a 4.6 m wide flail shredder (~10 cm height) and immediately raked into a single large windrow with a twin-rotor rotary rake (~5.8 m width) (Table 1). In 2002, 16 large square bales (Case IH[1] model 8575; 80 cm W × 88 cm H × 150 cm L bale size) and 16 large round bales were formed (John Deere[1] model 566; 150 cm W × 180 cm D bale size). In 2003, 16 round bales were formed each day using this same baler. All bales were weighed in the field to the nearest 0.5 kg using a 1800 kg capacity platform scale. All bales were bored once on each side to a depth of about 50 cm using a 5 cm diameter boring tube to collect material for moisture determination using the oven dry procedures described above. Relevant bale dimensions were measured for calculation of bale density. Bales were then wrapped in eight layers of 1-mil white plastic film using an H & S[1] model LW2 tube line wrapper. Large square bales were placed with their longitudinal axis perpendicular to the longitudinal axis of the tube. Total time and windrow distance covered to form each bale was determined to calculate yield and harvesting rate.

2.4. Baled stover—dry product

Grain harvesting took place on 10/17/02 and 10/10/03 prior to forming dry stover bales. The stover was allowed to sit for a few days and was then shredded using a 4.6 m wide flail shredder (~10 cm height) and placed in a wide swath (~4.5 m) (Table 1). In 2002, several rain events prevented baling until 11/27/02. The day before baling, a twin-rotor rotary rake (~5.8 m width) was used to form a single large windrow. In 2003, weather conditions favored rapid drying so the field was raked on 10/22/03. In both years, large square bales were formed (10 bales in 2002; 5 bales in 2003) with the same square baler described above. In 2002, large round bales were formed with a John Deere[1] model 456 (117 cm W × 152 cm D bale size) using either plastic twine (8 bales) or sisal twine (4 bales) on 15 cm spacing plus 6 end wraps or $2\frac{1}{2}$ layers of to-edge mesh wrap (16 bales). In 2003, round bales were formed with a John Deere[1] model 566 baler (150 cm W × 180 cm D) using plastic twine (12 bales) or sisal twine (12 bales) on 15 cm spacing plus 6 end wraps or $2\frac{1}{2}$ layers of to-edge mesh wrap (18 bales). All bales were weighed to the nearest 0.5 kg using a 1800 kg capacity platform scale. Other procedures used to collect and dry moisture samples, and to determine yield and harvest rate were similar to those described above. All large square bales and 8 (2002) or 6 (2003) net wrapped round bales were stored inside an open front hay shed. The remaining round bales were stored outside with half of each wrap type stored directly on the ground and half on a raised, well-drained surface (wooden pallets). The rows of round bales were placed on a level surface in a line running north–south with the ends butted tightly together with no obstructions to shade the bales.

2.5. Baled stover—removal from storage

All wet and dry bales were removed from storage on June 19th and 20th, 2003 (2002 bales) or June 28th and 29th, 2004 (2003 bales). Bales were weighed and bored for moisture samples using the same equipment and procedures described above. Before a bale was weighed, the vertical and horizontal diameters and the bottom length in contact with the soil were measured on both ends of the bale. Bore samples from several locations were collected from round bales stored outdoors to accurately assess the average bale moisture. Four samples were taken to a depth of about 30 cm, one from each side (defined as rind moisture) and two from the bottom of the bale (defined as bottom moisture). Two additional bore samples, one from each side, were taken from a depth range of 30–50 cm (defined as core moisture). The overall volume adjusted bale moisture was calculated using these moistures and the bale dimensions explained above.

2.6. Statistical analysis

Differences between treatments in individual experiments were analyzed using analysis of variance and statistical differences were determined using a least-significant-difference test (LSD) at the 95% confidence level.

3. Results and discussion

3.1. Stover drying characteristics after grain harvest

In 2002, field drying conditions were very challenging during the 3 weeks after grain harvest. Rain fell on 10 of the 23 days during the first study, with a total precipitation of 25 mm (Fig. 1(a)). The average daytime temperature during the drying study was 5 °C. These were about average conditions for Arlington, Wisconsin during mid- to late-October (40 mm precipitation; 9 °C). It is generally accepted that bale moisture needs to be less than 20% (wet basis) to prevent significant biological activity during storage [10]. Only during one brief period in the first study did the moisture of 2 of the treatments approach this desired moisture range (Fig. 1(a)) and that occurred 5–7 d after grain harvest. In the second study, none of the treatments approached the desired moisture range during the 10 d drying period (Fig. 1(b)). In 2003, field drying conditions were initially quite good and the treated stover dried to less than 20% moisture in about 4 d (Fig. 2(a)). When several rain events occurred after shredding, none of the treatments reached this moisture after 10 d (Fig. 2(b)).

Mechanical conditioning in the form of flail shredding improved the drying rate when the crop was placed in a wide swath behind the shredder (Figs. 1(a) and 2(b)). This occurred because the flail shredder split the stalk open, which allowed the trapped moisture in the stalk pith to more readily escape. Placing the shredded material in a narrow windrow at shredding is desirable because this practice would eliminate the need for raking prior to baling. Raking not only adds another field operation, but also increases the chance of soil and rock contamination. However, when weather conditions were poor, windrowing at shredding reduced the drying rate, retarding it to the extent that the unconditioned control actually dried at a faster rate, especially when a double-density windrow was formed (Figs. 1(a) and 2(b)). The windrow density was such that air movement was probably restricted and the bottom material shaded. When rain events occurred, the shredded treatments were more affected than the untreated treatments (Figs. 1(a), (b) and 2(b)). This was presumably because the shredded treatments were laying close to the ground in a generally horizontal manner that promoted water sitting on the stover while a great majority of the untreated stover was still upright which allowed water to shed more easily. These results suggest that a device on the combine harvester that conditions the stalk but allows it to remain upright might enhance drying prior to a shredding operation that directly precedes baling. These results also suggest that delaying shredding after grain harvest until there is an anticipated stretch of good weather might enhance the possibility of achieving the desired moisture.

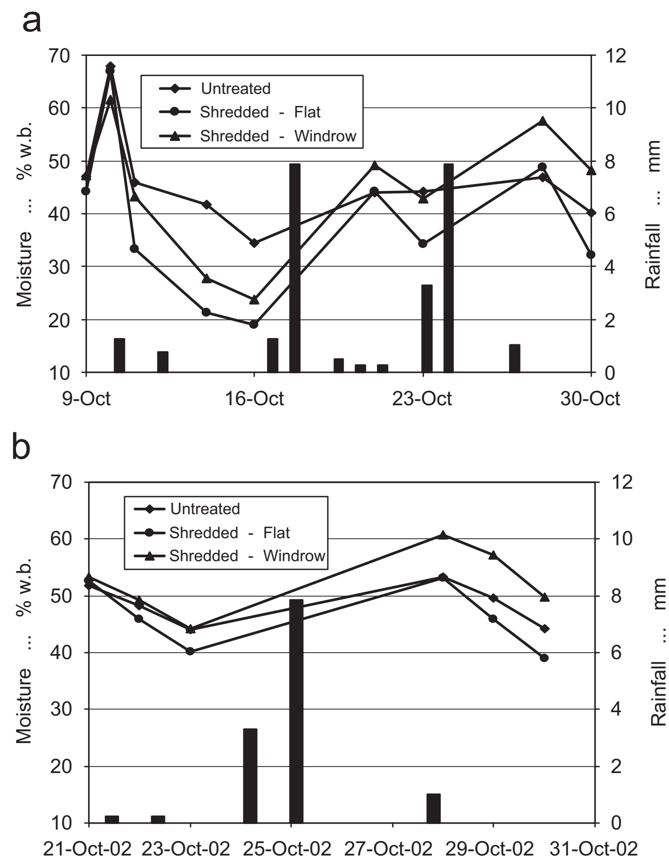

Fig. 1. Drying rate of stover after grain harvest as affected by three conditioning treatments in 2002 (magnitude of rainfall events indicated by vertical bar). Average high temperature during drying period was 5 °C (a) and 7 °C (b).

3.2. Chopped stover—wet product

In 2002, grain was harvested late in the afternoon. The stover fraction was shredded and double windrowed within an hour of grain harvest and then allowed to sit in the field until the next morning. The ambient conditions during that

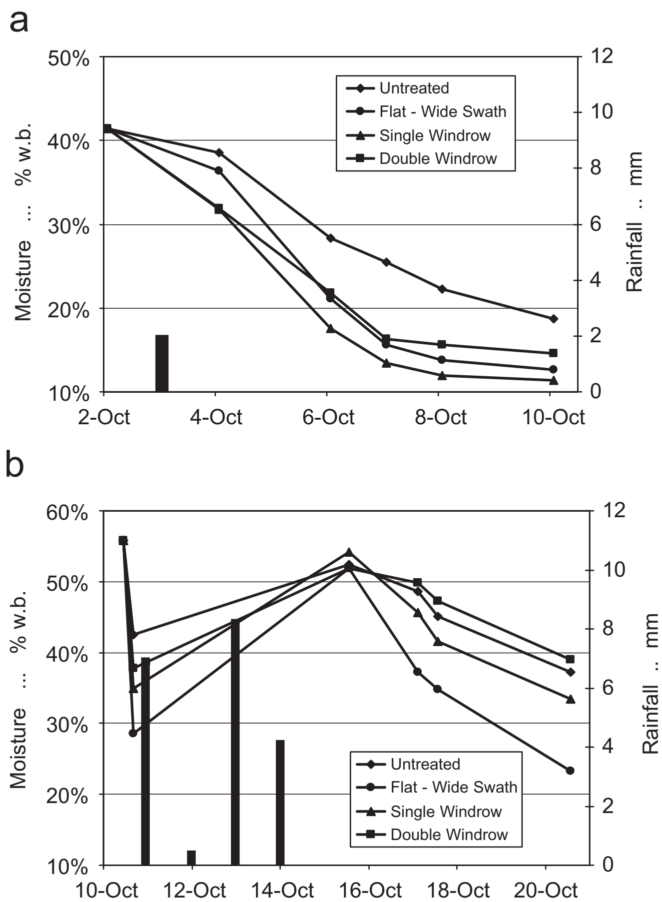

Fig. 2. Drying rate of stover after grain harvest as affected by four conditioning treatments in 2003 (magnitude of rainfall events indicated by vertical bar). Average high temperature during drying period was 19 °C (a) and 18 °C (b).

period were warm (11 °C) and very windy, so stover moisture dropped from 63% (w.b.) at grain harvest to 47% (w.b.) at chopping. In 2003, shredding and chopping took place within an hour of grain harvest and stover moisture dropped 4–5 percentage points from grain harvest to chopping (60 to 55% on 10/13 and 45 to 41% on 10/30).

The windrow proved to be quite difficult to pickup with the harvester's windrow pickup, which is normally intended for gathering alfalfa and grasses. These crops are intertwined and feed continuously into the pickup and feedrolls. The shredded stover was not intertwined, so the pickup teeth had difficulty gathering it. The only way to overcome these difficulties was to slow forward speed to about 4.0–5.5 km h^{-1}, so harvesting capacity was limited not by available power but by these gathering difficulties. The harvesting efficiency of shredding, windrowing and chopping was roughly 55% in both years (see footnote in Table 2), meaning that just over half the available stover mass was collected.

The average particle size of the chopped stover was considerably longer than the TLC (Table 2). The actual and theoretical particle size of whole-plant corn silage are typically quite similar because the crop is tall (> 1800 mm) and erect at harvest, it is cut directly from its root structure, and therefore, it is well metered by the chopper feedrolls and properly oriented to the cutterhead [11]. Shredded stover was short (170–290 mm, Table 2) and very chaotic in the windrow, so it was difficult to gather, meter and orient to the chopper cutterhead, so its final particle size was much longer than the TLC.

Density of alfalfa haylage and whole-plant corn silage was reported to range from 80 to 90 and 90 to 125 kg DM m^{-3}, respectively [12,13]. Average density of chopped corn stover was 71 kg DM m^{-3} (Table 2). This difference can be attributed to the low moisture and long particle size of the stover compared to typical silage crops. Stover also lacked the high density grain fraction found in whole-plant corn silage. Shipping volume and weight restrictions constrain the density in the truck to a maximum of about 240 kg WM m^{-3}. At the shortest TLC, stover density in the truck was 147 kg WM m^{-3}, well short of the desired target. Alternatives other than size reduction, such as compaction or chemical treatment, should be considered to achieve the desired shipping bulk density. Stover dry density in the bag silo averaged 140 kg DM m^{-3} (Table 2), well below that of alfalfa haylage (160–240 kg DM m^{-3}) and whole-plant corn silage (160–280 DM m^{-3}) in a silo bag [14]. Corn silage losses in bag silos are well correlated with silage density because of oxygen infiltration and subsequent biological activity [14].

Despite low dry bulk density, storing chopped wet stover in a bag silo was successful. The chopped material was removed from the bag after about 9 months of storage and had excellent appearance and color with a familiar, pleasant ensiled odor. Dry matter loss was 10.9% of total DM in 2002 (Table 3). It is unknown how much of this loss was due to respiration and biological activity and how much was due to lost material during loading and unloading the silo. The 4.4% unit rise in moisture during storage shows that some biological respiration did occur (Table 3). In 2003, DM loss averaged 2.6% with only small changes between initial and final moisture (Table 3). Losses of chopped whole-plant corn silage stored in bag silos averaged 15% and were dependent upon moisture, packing density and feed-out rate [14]. One reason for the low stover DM losses relative to ensiled animal feed is the manner in which stover was removed. Ensiled animal feed is metered out daily so that the face is exposed to oxygen infiltration and biological degradation over a long period. Face losses were not experienced here because the ensiled stover was removed all in one day, a practice that would be common if stover served as a biomass feedstock.

When moisture was above 50% (w.b.), silage fermentation was quite good, with reasonable pH and lactic and acetic acid production (Table 3). However, fermentation products were lower and pH higher for the stover than would typically be expected of whole-plant corn silage. Typical whole-plant corn silage would have a pH of about 4.0 and acid levels of 2.0% and 7.5% of DM for acetic and

Table 2
Productivity and physical properties of corn stover harvested as chopped material using precision-cut forage harvester and ensiled in plastic silo bags[a,b]

Length-of-cut	Moisture (% w.b.)	Harvester mass flow		Density in truck		Density in silo bag		Final particle-size (mm)
		Wet ($Mg\,h^{-1}$)	Dry ($Mg\,h^{-1}$)	Wet ($kg\,m^{-3}$)	Dry ($kg\,m^{-3}$)	Wet ($kg\,m^{-3}$)	Dry ($kg\,m^{-3}$)	
2002								
6.4 mm	48.4	49.1	25.9	158_b	82_b	288	150	17.8
12.7 mm	47.9	53.7	28.0	134_a	69_a	301	157	25.4
19.1 mm	45.8	55.5	30.1	126_a	67_a	286	150	27.9
LSD[c] ($P = 0.05$)	4.1	14.3	9.1	18	5	91	43	NA
2003								
6.4 mm	49.6	40.8	20.2_a	136	67	261	130	20.3_a
12.7 mm	48.0	51.3	26.0_b	131	69	251	128	22.9_b
19.1 mm	45.8	51.3	26.8_b	128	69	240	122	27.9_b
LSD[c] ($P = 0.05$)	6.5	11.1	4.2	24	13	75	37	2.5

[a]In 2002, particle size of stover before shredding and chopping was 690 mm and after shredding but before chopping was 290 mm. Stover yield was 9.2 Mg DM ha^{-1} just preceding grain harvest. Average harvested yield after shredding, windrowing and chopping was 4.9 Mg DM ha^{-1}.
[b]In 2003, particle size of stover before shredding and chopping was 610 mm and after shredding but before chopping was 172 mm. Stover yield was 10.5 Mg DM ha^{-1} just preceding grain harvest. Average harvested stover yield after shredding, windrowing and chopping was 5.8 Mg DM ha^{-1}.
[c]Averages with different subscripts in the same column are significantly different at 95% confidence.

Table 3
Final storage data for chopped wet stover stored in a plastic bag silos for approximately nine months[a]

	Initial moisture (% w.b.)	Final moisture (% w.b.)	DM loss (% of total)	pH	Fermentation products (% of DM)				Composition (% of DM)		
					Lactic acid	Acetic acid	Butyric acid	Ethanol	Nitrogen	ADF	NDF
2002–03	47.3	51.7	10.9	4.1	3.66	1.01	0	0.26	—	—	—
2003–04	55.4	55.7	3.8	4.1_a	3.29_b	0.91_b	0	0	0.66_b	41.1_a	66.9_a
2003–04	41.7	39.9	1.4	4.5_b	1.69_a	0.57_a	0	0	0.54_a	42.8_b	69.5_b
LSD[b] ($P = 0.05$)				0.3	0.56	0.17	—	—	0.05	0.3	0.7

[a]In storage from 10/9/02 to 7/8/03 (272 d); from 10/13/03 to 7/23/04 (284 d); and from 10/30/03 to 7/23/04 (267 d).
[b]Averages with different subscripts in the same column are significantly different at 95% confidence. Statistical analysis only conducted for data collected in 2003.

lactic acids, respectively. These differences would be attributed to the low initial stover moisture and the lack of the corn grain which acts as an important fermentation substrate.

Several random grab samples of the stover were hand separated into 5 plant fractions after storage and compared to the fractions found prior to and after grain harvest. The proportion of stalk in the shredded and chopped stover dropped because about 15 cm of stalk remained standing after shredding (Table 4). Harvesting at that height also left a considerable fraction of the cobs, which tended to fall to the soil surface when ejected from the combine and were difficult to gather with the flail shredder. Leaves and husk were light and more easily gathered by the vacuum action of the flail shredder.

3.3. Baled stover—wet product

In 2002, the stover fraction was shredded and windrowed within an hour of grain harvest and then raked into double windrows within an hour of shredding. The ambient conditions during that period were quite warm (14 °C) and windy, so stover moisture dropped from 63% (w.b.) at grain harvest to 39% (w.b.) at baling. When more typical fall conditions prevailed (2003), stover moisture was 51% at grain harvest and 44% at baling.

The pickup on both the round and square balers experienced the same difficulty in gathering the shredded stover as was experienced with the forage harvester (described above). Therefore, the capacity of the balers was not limited by power or baling ability but by gathering

Table 4
Portion of total corn plant contained in each of the five plant fractions prior to grain harvest, after grain harvest and after stover harvest with a forage harvester

	% of total DM		
	Standing crop prior to grain harvest	After grain harvest[a]	After stover harvest[b]
Grain	51.4	3.1	1.4
Cob	6.1	12.2	3.2
Husk	4.2	8.4	10.4
Leaf	9.3	18.5	36.1
Stalk	29.0	57.8	48.9

[a]Prior to shredding and chopping.
[b]After shredding and chopping.

Table 5
Productivity and physical properties of wet corn stover harvested as baled material using large round or large square balers and ensiled in plastic film wrap

	Moisture (% w.b.)	Baler mass-flow		Bale density		Harvested yield[a]	
		Wet ($Mg\,h^{-1}$)	Dry ($Mg\,h^{-1}$)	Wet ($kg\,m^{-3}$)	Dry ($kg\,m^{-3}$)	Wet ($Mg\,ha^{-1}$)	Dry ($Mg\,ha^{-1}$)
2002							
LRB[b]—Twine	37.9	18.0_a	11.2_a	176_a	109_a	6.7_a	4.3_a
LSB[b]	39.9	34.7_b	20.9_b	248_b	149_b	9.0_b	5.4_b
LSD[c] ($P = 0.05$)	2.9	2.5	1.6	13	6	0.9	0.5
2003							
LRB[b]—Net	36.8	21.9_b	13.6_b	186	117	9.0	5.7
LRB[b]—Twine	36.8	16.1_a	10.2_a	190	118	8.5	5.4
LSD[c] ($P = 0.05$)	6.3	2.4	1.2	16	10	1.8	0.7

[a]Stover yield of standing plant material was 8.6 Mg DM ha^{-1} just preceding grain harvest in 2002 and 11.3 Mg DM ha^{-1} in 2003.
[b]LRB: large round bales; LSB: large square bales.
[c]Averages with different subscripts in the same column are significantly different at 95% confidence.

limitations. In 2002, the harvesting efficiency of shredding, raking and baling was 50% and 63% for the large round and large square balers, respectively (see footnote Table 5). Round baler harvesting efficiency was also about 50% in 2003 (Table 5). The pickup for the large square baler was wider than that for the round baler which likely accounted for differences in harvesting efficiency between machines.

There were no difficulties with wrapping either bale type with plastic film. The large square bales of stover had 37% greater dry density than round bales (2002 only). Alfalfa bale densities at 35–45% moisture were 151 and 177 kg DM m^{-3} for large round and square bales, respectively, a 17% difference [15]. Corn stover, even after shredding, had many large diameter, intact stalk sections that resisted the compression forces in either baler. Densities were therefore 16–28% less in stover than those reported in similar moisture alfalfa. Harvesting machines and systems that help to further break down the mechanical structure of the stover could enhance bale density when using either baler type.

The productivity of the large square baler was almost double that of the round baler (2002 only). About 25% of the round baling time was spent at idle while wrapping with twine, which greatly reduced productivity. The square baler pickup had faster tip speed and had greater width, so baler forward speed was slightly higher for this baler. Average ground speed during baling was 3.5 and 4.2 km h^{-1} for the large round and square balers, respectively (2002 only). Round baler productivity was improved 36% when net wrap was used instead of twine due to the reduction in the required time to wrap (Table 5). Similar productivity improvements were reported when baling alfalfa [15]. There were no significant differences in bale density between the round bale wrap types (Table 5).

Storing wet stover bales by wrapping and ensiling was quite successful. Bales were removed from the tube after about 8 months of storage and the bales had excellent appearance and color with a familiar, pleasant ensiled odor. There were no statistical differences in DM loss between large square and round bales or between twine and net wrapped round bales (Table 6). Alfalfa bales wrapped in film tubes at 35–57% moisture had DM losses of 2.2–6.8% with no trend over several trials for one bale type to have lower losses than the other [15]. The average DM

Table 6
Final storage data for wet stover bales wrapped in a tube of plastic film after approximately eight months of storage[a]

	Initial moisture (% w.b.)	Final moisture (% w.b.)	DM loss (% of total)	pH	Fermentation products (% of DM)			
					Lactic acid	Acetic acid	Butyric acid	Ethanol
2002								
LRB[b]—Twine	37.9	38.9	3.0	5.3	1.19	0.77	0	0.31
LSB[b]	39.9	40.7	4.2	4.8	1.73	0.79	0	0.46
LSD[c] ($P = 0.05$)	2.9	3.7	2.7	0.8	0.82	0.14	—	0.25
2003								
10/24[d]	29.4_a	29.5_a	1.2	5.1_b	0.48_a	0.39_a	0	0.15_b
10/30[d]	44.3_b	45.6_b	2.9	4.4_a	2.29_b	0.78_b	0	0.00_b
LSD[c] ($P = 0.05$)	2.8	2.6	2.1	0.2	0.66	0.11	—	0.03

[a]In storage from 10/11/02 to 6/19/03 (251 d); from 10/24/03 to 6/28/04 (248 d); and from 10/30/03 to 6/28/04 (242 d).
[b]LRB: large round bales; LSB: large square bales.
[c]Averages with different subscripts in the same column are significantly different at 95% confidence.
[d]Date on which bales were formed.

Table 7
Productivity and physical properties of dry corn stover harvested as baled material using large round or large square balers and stored indoors and outdoors

	Moisture (% w.b.)	Baler mass-flow		Bale density		Harvested yield[a]	
		Wet ($Mg\,h^{-1}$)	Dry ($Mg\,h^{-1}$)	Wet ($kg\,m^{-3}$)	Dry ($kg\,m^{-3}$)	Wet ($Mg\,ha^{-1}$)	Dry ($Mg\,ha^{-1}$)
2002							
LRB[b]—Twine	23.0	6.8_a	5.2_a	123_a	94_a	4.7_b	3.6_b
LRB[b]—Net	23.5	7.3_a	5.5_a	138_b	106_b	2.9_a	2.2_a
LSB[b]	24.0	17.2_b	13.1_b	178_c	134_c	4.3_b	3.1_b
LSD[c] ($P = 0.05$)	3.5	2.4	1.8	8	6	0.7	0.5
2003							
LRB[b]—Twine	15.7_{ab}	11.2_a	9.5_a	139_a	118_a	5.4	4.7
LRB[b]—Net	17.0_b	16.5_b	13.7_b	138_a	114_a	5.6	4.7
LSB[b]	14.6_a	16.3_b	14.0_b	150_b	128_b	5.4	4.7
LSD[c] ($P = 0.05$)	1.3	0.9	0.8	8	6	0.4	0.4

[a]In 2002, stover was harvested about 1 month after grain harvest and stover yield was 8.9 Mg DM ha^{-1} just preceding grain harvest. In 2003, stover was harvested within 1 week of grain harvest and stover yield was 11.6 Mg DM ha^{-1} just preceding grain harvest.
[b]LRB: large round bales; LSB: large square bales.
[c]Averages with different subscripts in the same column are significantly different at 95% confidence.

loss for ensiled stover bales was 2.9%, about the same as for dry stover bales stored indoors (see below).

The low levels of acids and relatively high pH of the wrapped stover bales indicate that very little fermentation actually took place. However, DM losses were quite low, indicating that stover can be very well preserved with limited fermentation as long as the plastic film limits oxygen infiltration. There were no statistical differences in fermentation products between bale types but higher-moisture bales produced significantly greater levels of fermentation products than low-moisture bales (Table 6).

Large square bales required almost twice the mass of plastic film per kg DM compared to large round bales, primarily because the surface-to-volume ratio favors the latter bale configuration [15]. So although the large square bale offers productivity and density advantages, wrapping strategies, such as stacking bales before wrapping or using larger bale cross-sections, need to be investigated to reduce plastic film requirements.

3.4. Baled stover—dry product

In 2002, bales were formed almost 6 weeks after grain harvest and shredding because of frequent rain or snow during the field drying period. Therefore, the physical condition of the stover had somewhat deteriorated by the time baling occurred. The problems with poor gathering with the baler pickups were even more evident with this stover, so baling speed was limited to 2.7 and 3.8 $km\,h^{-1}$ for the large round and square balers, respectively (Table 7). In 2003, stover was harvested within a week of grain harvest and shredding and the stover physical condition was excellent. Although gathering still limited baling speed, baler productivity in 2003 was similar between wet and dry stover (Tables 5 and 7) and these values should be considered typical.

In 2002, large round and square dry bales were 13% and 10% less dense, respectively, on a DM basis than wet stover bales (Tables 5 and 7). The reduction in bale density for both bale types might be due to the poor physical condition of the dry stalks at the time of baling. In 2003, bale density was similar for wet and dry stover (Tables 5 and 7) and these values should be considered typical. Large square bales had about 9% greater density than round bales. The harvesting efficiency of shredding, raking and baling dry stover was roughly 33% and 41% for the 2002 and 2003, respectively, which was considerably lower than that for wet stover at 57% and 50%, respectively. One reason for this difference was that the dry stover was harvested well after grain harvest and losses from wind and biological degradation probably occurred. It was also observed that wet stover was more readily retrieved by the baler pickup than dry stover. The results suggest that yield and harvesting efficiency decrease as the time delay between grain and stover harvest increases. In 2002, the delay between grain harvest and wet or dry stover harvest was 1 and 42 d, respectively, and harvesting efficiency fell from 57% to 33%, respectively. In 2003, the delay between grain harvest and wet or dry stover harvest was 1 and 7 d, respectively, and harvesting efficiency dropped from 50% to 41%, respectively.

The 10-yr historical average precipitation in Arlington, Wisconsin during the storage period is 455 mm [16]. Total precipitation during the storage period was 235 mm in 2002–03 and 734 mm in 2003–04, with 320 mm in the last 6 weeks of storage in 2004. Sisal twine wrapped bales had greater DM loss than bales wrapped with plastic twine or net wrap primarily because the sisal twine rotted away at the base of the bale (Table 8). When sisal twine bales were lifted from storage, stover that sloughed from the base of the bale was not recoverable. Unrecoverable material was considered part of the DM storage loss. In 2002–03, when precipitation was less, it was observed that the sisal twine had fewer tendencies to rot away when stored on pallets and that some bales maintained their integrity throughout storage, decreasing DM loss compared to storing on the ground (Table 8). However, in 2003–04, when precipitation was above normal, all the sisal twine rotted away no matter if stored on the ground or pallets. Independent of storage method, net wrapped bales had about 62% and 31% (2002) or 70% and 25% (2003) lower DM losses than bales wrapped with sisal or plastic twine, respectively. Net wrapped bales almost always had significantly lower moisture in the rind than either type of twine wrapped bales (Table 8), which likely contributed to lower DM loss. Storing bales on pallets reduced DM losses for all treatments because water was able to drain away from the bales resulting in lower moisture in the base of the bales. These results were similar to those reported for bales of alfalfa or alfalfa/grass mixes [15].

Storing dry bales indoors significantly reduced DM loss compared to all other treatments (Table 8). Average DM loss of large square and round bales stored inside was slightly less than 5% in 2002 and about 2% in 2003. The lower initial bale moisture in 2003 probably contributed to less biological activity in storage and the lower losses. There was no significant difference in losses between bale types stored indoors (Table 8). The moisture of the bales stored indoors was significantly lower compared to all outdoor treatments, which contributed to the lower DM loss because biological activity was less. Bales stored indoors also were not subject to leaching losses during precipitation. The DM loss of net wrapped round bales stored indoors was 45% less than the average DM loss of net wrapped bales stored outdoors.

4. Conclusions

- Stover drying was challenged by low ambient temperatures and frequent precipitation so that only in one out of four trials did stover dry to baling moisture (~20%) within 4 d of grain harvest.
- Harvesting efficiency, i.e. the ratio of stover mass actually harvested to mass available in the field, averaged 55, 50 and 37%, respectively, for chopping, wet baling and dry baling.
- Harvesting capacity was 26.2, 16.0 and 9.8 Mg DM h^{-1} when harvesting shredded stover with a forage harvester, large square baler and large round baler, respectively. In all cases, capacity was limited by difficulty in gathering shredded stover at the pickup.
- Chopped stover density was 71 kg DM m^{-3} in the truck and 140 kg DM m^{-3} in the bag silo. Actual particle-size was considerably longer than theoretical length-of-cut.
- After 9 months, average storage DM loss was 5.4% for chopped/bagged stover (49% moisture) and 2.4% for baled/wrapped stover (38% moisture). Stover pH was 4.3 for chopped/bagged stover and 4.9 for baled/wrapped stover, with low levels of fermentation products in both cases.
- After 8 months, average storage DM loss was 3.3% for dry stover bales stored indoors and 18.1% for bales stored outdoors. Average DM loss for bales stored outdoors was 10.0%, 13.9% and 30.4% for bales wrapped with net wrap, plastic twine and sisal twine, respectively. At removal, total bale moisture was significantly lower for net compared to twine wrapped bales (38.9% vs. 48.8%). Independent of wrap type, moisture of the rind, core and base averaged 49.7%, 21.5% and 46.9%, respectively, with a volume adjusted total average moisture of 42.9%.

Table 8
Storage characteristics of dry corn stover bales stored for approximately seven or eight months[a,b]

Storage Location	Wrap and/or Bale Type	2002						2003					
		Moisture (% w.b.)					DM loss (% of total)	Moisture (% w.b.)					DM loss (% of total)
		Initial	Final					Initial	Final				
			Rind	Core	Base	Volume adjusted total			Rind	Core	Base	Volume adjusted total	
Inside													
	Large round	25.9_{bc}	—	—	—	19.2_{a}	4.9_{a}	16.4_{bc}	—	—	—	13.6_{a}	2.2_{a}
	Large square	23.9_{ab}	—	—	—	19.3_{a}	4.8_{a}	14.6_{a}	—	—	—	13.2_{a}	1.1_{a}
Outside on ground[c]													
	Sisal twine	32.0_{d}	46.8_{b}	20.4_{bc}	48.0_{c}	37.7_{d}	29.1_{e}	15.6_{ab}	54.5_{a}	23.2_{a}	63.0_{c}	54.0_{c}	38.5_{d}
	Plastic twine	24.4_{abc}	46.2_{b}	22.6_{c}	37.5_{bc}	36.4_{d}	14.3_{c}	16.6_{bc}	64.6_{b}	32.7_{b}	62.6_{bc}	59.1_{d}	19.0_{c}
	Net wrap	22.2_{a}	35.8_{a}	18.9_{abc}	38.5_{c}	30.3_{c}	10.7_{bc}	16.4_{bc}	61.9_{b}	20.7_{a}	54.2_{a}	53.3_{c}	14.2_{c}
Outside on pallets[c]													
	Sisal twine	27.5_{c}	45.3_{b}	16.7_{ab}	28.3_{ab}	30.9_{c}	17.7_{d}	15.4_{ab}	54.0_{a}	24.3_{a}	70.8_{d}	55.4_{c}	36.1_{d}
	Plastic twine	23.0_{ab}	46.3_{b}	16.6_{a}	24.5_{a}	32.2_{c}	11.4_{c}	15.1_{ab}	61.4_{b}	22.5_{a}	56.4_{ab}	54.1_{c}	11.0_{b}
	Net wrap	22.3_{a}	27.1_{a}	18.1_{ab}	24.2_{a}	23.5_{b}	7.0_{ab}	18.1_{c}	52.9_{a}	21.1_{a}	54.3_{a}	47.9_{b}	8.2_{b}
	LSD[d] ($P = 0.05$)	3.5	9.3	3.7	11.2	3.3	4.3	1.7	5.1	5.8	6.4	3.0	5.6

[a]In storage from 11/27/02 to 6/20/03 (205 d); and from 10/22/03 to 6/29/04 (251 d).
[b]Total precipitation during storage period was 235 mm in 2002 and 734 mm with 320 mm in the last 6 weeks of storage in 2003.
[c]Only large round bales were stored outdoors.
[d]Averages with different subscripts in the same column are significantly different at 95% confidence.

- Harvesting wet stover right after grain harvest was timelier and resulted in greater harvesting rate and yield compared to dry stover harvest. Storing wet stover by ensiling resulted in lower losses and more uniform product moisture compared to dry stover bales stored outdoors.

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