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HARVEST AND STORAGE OF WET AND DRY CORN STOVER AS A BIOMASS FEEDSTOCK

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Abstract. *When corn grain moisture was in the typical harvest range of 30 and 20%, the ratio of stover dry mass to whole-plant dry mass averaged 43%. The moisture in the stalk remained over 65% until grain harvest. The ratio of mass of stover harvested to total stover DM yield, averaged about 53, 56 and 33% for chopping, wet baling and dry baling, respectively. Harvesting wet stover as chopped material and ensiling in a silo bag was successful with DM matter loss at 10.9% after seven months storage. Harvesting wet stover by baling and tube wrapping was also successful with DM loss of 3.6%. Dry stover bales stored indoors and outdoors had average DM losses of 5 and 15%, respectively. Wrapping dry bales in net wrap and storing on a well drained surface significantly reduced DM loss compared to storing twine wrapped dry bales on the ground.*

Keywords. Biomass, corn stover, harvesting, silage, storage.

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Abstract

Corn stover is an ideal biomass feedstock but the harvest and storage of this material presents many challenges. Information on the physical properties of stover and the operational and functional analysis of various harvesting methods is important to improve the efficiency and economics of corn stover harvest and storage. When corn grain moisture was in the typical harvest range of 30 and 20%, the ratio of stover dry mass to whole-plant dry mass averaged 43% and grain and stover yields averaged 13.0 and 9.8 Mg/ha (5.4 and 4.1 ton/ac), respectively. The moisture in the total stover fraction was between 65 and 58% when grain moisture was between 30 and 20%. The moisture in the stalk remained over 65% until grain harvest. The ratio of mass of stover harvested to total stover DM yield, i.e. the harvesting efficiency, averaged about 53, 56 and 33% for chopping, wet baling and dry baling, respectively. Harvesting wet stover as chopped material and ensiling in a silo bag was successful with DM matter loss at 10.9% after seven months storage. Harvesting wet stover by baling and tube wrapping was also successful with DM loss of 3.6%. Dry stover bales stored indoors and outdoors had average DM losses of 5 and 15%, respectively. Average DM loss for bales stored outdoors was 8.9, 13.3 and 23.4% for bales wrapped with net wrap, plastic twine and sisal twine, respectively. Independent of wrap type, the average DM loss was 18.0 and 12.0% for bales stored outdoors on the ground and outdoors on a well drained surface, respectively.

Background

There is increased emphasis on renewable energy and environmental sustainability by the conversion of biomass to transportation fuel, electricity, and industrial products. The Biomass Research and Development Board (2001) projects a three-fold increase in bio-ethanol, bio-diesel, bio-electricity, and emerging bio-based products over the next decade. It is estimated that in 2020 over 500 million tons of bio-based feedstock will be required annually to meet the energy needs of the US without increases in imported energy (Sokhansanj and Wright, 2002). Alternative feedstocks such as corn stover for ethanol could help meet the increased demand for renewable resources. Because of its abundance and proximity to existing grain-to-ethanol conversion facilities, corn stover has been suggested as an ideal strategic feedstock to increase ethanol production using cellulosic conversion processes (Hettenhaus and Wooley, 2000). 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 stover is quite high. Three major uses of corn stover as a bio-based commodity are envisioned:

- Enzymatic hydrolysis of cellulose to fermentable sugars to produce ethanol fuel.
- Direct combustion or gasification to produce electricity at power plants.
- Processing of specific fractions into a supplemental fiber source for paper pulp.

Corn stover has value to the corn producer. It serves as surface cover for erosion control and moisture retention and also has soil nutrient value, particularly P and K. However, corn stover slows soil warming and requires soil incorporation by tillage, an expensive field operation. It has been estimated that corn stover could have a value of \$35 to \$60 per dry ton dependent upon the intended target of the material (Hettenhaus and Wooley, 2000). There would be additional improvements in potential income per acre if tillage costs could be reduced due to the lower residue level. Costs associated with harvesting corn stover would include packaging, handling, and transporting. Additional costs are incurred due to the need for added fertilizer inputs. The costs of harvesting, handling and transporting biomass over a distance of 5 miles using current equipment technology was estimated at about $20 per dry ton (Sokhansanj and Turnhollow, 2002). The cost to replace the fertilizer value of biomass has been estimated at about $3 per dry ton removed (Hettenhaus and Wooley, 2000).

The yield of corn stover removed from the field will be dependent upon overall crop yield, amount needed for erosion control and soil tilth, and the type of harvesting/collection system used. Assuming a typical range of corn grain for the Upper Midwest and typical stover yields and moistures, the range of gross income would be about $131 to 173/ha ($53 to $70/ac). The cost for additional fertilizer and for harvesting stover would range from $86 to $114/ha ($35 to $46/ac). The net income would then range from $44 to 59/ha ($18 to $24/ac) independent of transportation cost (Hettenhaus and Wooley, 2000; Sokhansanj et al., 2001). If the average haul distance was 16 km (10 mi) at $1 per loaded km ($1.50/mi), then net-net income would be $32 to $47/ha ($13 to $19/ac). Additional income could be generated if removal of the residue reduced the total number of tillage operations required. Clearly, net income for corn stover harvest could be improved by reducing the costs associated with harvesting, handling, and transporting.

There is limited technical data concerning the harvesting and handling of corn stover on a large scale. Some research has been conducted in this area by Edens et al. (2002); Montross et al. (2002) and Pordesimo et al. (2002). Research is needed to address timeliness, productivity, drying rate, moisture, soil contamination, and storage losses under typical Upper Midwest conditions.

Objectives

The specific objectives of this research were:

- To determine the yield and moisture of the various fractions of the corn plant before grain harvest.
- To determine the drying rate of corn stover after grain harvest as affected by harvest date and conditioning treatment.
- To determine the field performance and storage characteristics of harvesting wet corn stover by chopping and storing in a bag silo or by baling and wrapping in plastic film.
- To determine the field performance and storage characteristics of harvesting dry corn stover and packaging in large round or square bales and storing inside or outdoors.

Procedures

Yield and Moisture Characteristics

Four different corn hybrids grown in five separate fields were evaluated for yield and moisture during a 50-day period from August 28th to October 16th, 2002 (table 1). The average field size was about 5 ha (13 ac) and the crop was grown on 76-cm (30-in.) row spacing. Target plant population was about 79,000 seeds/ha (32,000 seeds/ac) for all varieties and fields. Approximately every five days, five plants per field were harvested by hand cutting at about 10-cm (4-in.) from the ground. Plants were selected in an approximate "X" pattern in the field, i.e. one plant from the center and one each from the center of each quadrant. The five plants were pooled together each day to form a representative sample of each field. The plants were transported to a laboratory and hand separated into five fractions: grain, cob, husk, leaf and stalk. The leaf sheath was assumed to be part of the stalk. The stalk was further subdivided into quarters by length and identified as top, mid-top, mid-bottom and bottom fractions. All sub-fractions, except the grain, were size-reduced by chopping with a laboratory-scale cutterhead set to a TLC of 12-mm (½-in.) The mass of the entire contents of all sub-fractions was determined before and after oven drying at 103ºC (217ºF) for 24-h in accordance with ASAE Standard S318.2 (ASAE, 2002). Plant population was determined by counting the number of plants in several random 30-m (100-ft.) rows in each field. The yield of each fraction was determined by multiplying the mass by the measured plant population.

Table 1. Corn crop information concerning the five fields used in the stover yield and moisture studies conducted in 2002.

Variety	CRM*	Dates		Final Population	
	days	Planting	Harvest	plants/ha	(plants/ac)
Pioneer 35R58	105	5/3	10/17	62,165	25,170
Kaltenberg 6789	108	4/23	"	79,380	32,140
" "	"	"	10/8	74,600	30,200
Agri-Gold 6382	102	4/26	10/19	77,830	31,510
DeKalb 570RR	101	"	10/11	61,690	24,970

* Wisconsin Comparative Relative Maturity Index (Lauer, 1998)

Stover Field Drying Characteristics After Harvesting

Two drying trials were conducted in the fall of 2002: one that commenced on 10/9 and another on 10/21. Within several hours of harvest of the grain fraction with a conventional combine harvester, a portion of a field was subdivided into blocks and the following three treatments applied to each block: untreated, shredded and laid full-width, and shredded and windrowed. Each treatment was replicated with four blocks at each trial and the three treatments were randomly assigned within each block. The formed windrow was about 1-m (3-ft.) wide by 100-m (300 ft.) long. The only wheel traffic allowed in the field during harvest was that of the harvester. Shredding was accomplished with a 4.6-m (15-ft.) wide Buffalo model 4915 flail shredder equipped with windrow forming shields. The shredder was operated at about 10-cm (4-in.) from the soil at a speed of about 6.5 km/h (4.0 mi/h).

Samples for moisture determination were collected the day the sub-plots were formed and daily for three days after that. Samples were collected sporadically after that as weather permitted, but typically samples were collected every two or three days for up to 20 days after grain harvest. One sub-sample was collected from each sub-plot by gathering by hand all the material in an area about 0.5-m^2 (6-ft.^{2}) that spanned across two rows. Samples were placed in plastic bags, transported to a laboratory, sized reduced as described above, and the entire sub-sample oven dried at 103ºC (217ºF) for 24-h in accordance with ASAE Standard

S318.2 (ASAE, 2002). Weather data such as temperature and precipitation were recorded during the drying periods on an automated weather station maintained by experiment station personnel.

Harvesting and Storing Wet Stover – Chopped and Bagged

A 6-ha (15-ac) field was harvested on 10/8/02 using a conventional combine harvester. No other traffic was allowed on the field prior to shredding. Within several hours of grain harvesting the remaining stover was shredded and windrowed using a 6-m (20-ft.) wide Hiniker model 5600 flail shredder set to operate at about 15-cm (6-in.) from the soil. The shredder had an attachment that allowed a windrow to be formed on the far right-hand side of the machine. On the subsequent pass in the opposite direction, another windrow was placed immediately adjacent to the first. This doubling of windrows was performed to match the capacity needs of the forage harvester. The shredded and windrowed stover was allowed to sit overnight and harvesting commenced the next day. A John Deere model 6950 self-propelled forage harvester equipped with a 4.5-m (15-ft.) wide model 645 windrow pick-up was used to gather and chop the stover. The harvested material was collected in a Miller Pro model 4012 side-dumping forage container specially equipped with load cells to determine harvested mass. The material was dumped into straight-axle trucks, the load leveled by hand and the height from the top of the truck measured to determine volume occupied by the stover. The harvested mass and transport volume were used to calculate chopped stover density. The forage harvester was used to harvest 15 loads, five each at 6.4, 12.7 and 19.1-mm (0.25, 0.50 and 0.75-in.) TLC. The total time required to harvest a load was also recorded so that harvesting rate could be determined. The material was then unloaded into a Kelly Ryan silo bagger and placed in a 2.4-m (8-ft.) diameter plastic silo bag. The location of each load was marked on the bag and later the length and diameter of the bag at each load was determined so that silo density could be calculated. Prior to placing in storage, sub-samples were collected for moisture and particle-size determination. Moisture was determined on three sub-samples per load by oven drying at 103ºC (217ºF) for 24-h in accordance with ASAE Standard S318.2 (ASAE, 2002). Particle-size was determined on three sub-samples per TLC in accordance with ASAE Standard S424.1 (ASAE, 2002). In addition, particle-size was determined on two sub-samples of the untreated and shredded stover prior to chopping.

Harvesting and Storing Wet Stover – Baled and Wrapped

A 3-ha (7-ac) field was harvested on 10/11/02 using a conventional combine harvester. No other traffic was allowed on the field prior to shredding. Within an hour of grain harvesting the remaining stover was shredded and windrowed using a 4.6-m (15-ft.) wide Buffalo model 4915 flail shredder set to operate at about 10-cm (4-in.) from the soil. A Kuhn model GA7301 twin-rotor rotary rake was then used to merge two windrows into one to match the capacity needs of the balers. Large square bales were formed with a Case IH model 8575 baler (80-cm W x 88-cm H; 31.5-in. W x 34.5-in. H) set to deliver bales about 150-cm (60 in.) in length. Large round bales were formed with a John Deere model 566 (150-cm W x 180-cm ϕ; 60-in. W x 72-in. ϕ) using sisal twine on 15-cm (6-in.) spacing plus six end wraps. All bales were weighed in the field to the nearest 0.5 kg (1 lb.) using a 1,800 kg (4,000 lb.) capacity platform scale. All bales were bored once on each side to a depth of about 50-cm (20-in.) using a 5-cm (2-in.) diameter boring tube to collect material for moisture determination. Moisture samples were oven dried at 103ºC (217ºF) for 24-h in accordance with ASAE Standard S318.2 (ASAE, 2002). Relevant bale dimensions were measured in the field to allow calculation of bale density. Bales were then wrapped in eight layers of 1-mil white plastic film using an H & S model LW2 tube line wrapper. Large square bales were placed with their longitudinal axis perpendicular to the longitudinal axis of the tube. A total of 16 large round and 16 large square bales were formed and wrapped. Total time to form each bale and distance covered to form each bale were determined during formation in order to calculate yield and harvesting rate.

Harvesting and Storing Dry Stover – Baled

A 3.7-ha (9-ac) field was harvested on 10/17/02 using a conventional combine harvester. No other traffic was allowed on the field prior to shredding. The stover was allowed to sit for a few days and then was shredded and windrowed using a 4.6-m (15-ft.) wide Buffalo model 4915 flail shredder set to operate at about 10-cm (4-in.) from the soil. Several rain events prevented baling until 11/27/02. The day before baling, a Kuhn model GA7301 twin-rotor rotary rake was used to invert and merge two windrows into one to aid in final drying and to match the capacity needs of the balers. Large square bales were formed with a Case IH model 8575 baler (80-cm W x 88-cm H; 31.5-in. W x 34.5-in. H) set to deliver bales about 200-cm (80 in.) in length. Large round bales were formed with a John Deere model 456 (117-cm W x 152-cm ϕ; 46-in. W x 60-in. ϕ) using either plastic twine on 15-cm (6-in.) spacing plus six end wraps or 2½ layers of to-edge mesh wrap. All bales were weighed in the field to the nearest 0.5 kg (1 lb.) using a 1,800 kg (4,000 lb.) capacity platform scale. All bales were bored once on each side to a depth of about 50-cm (20-in.) using a 5-cm (2-in.) diameter boring tube to collect material for moisture determination. Moisture samples were oven dried at 103ºC (217ºF) for 24-h in accordance with ASAE Standard S318.2 (ASAE, 2002). Relevant bale dimensions were measured in the field to allow calculation of bale density. Total time to form each bale and distance covered to form each bale were determined during formation in order to calculate yield and harvesting rate. A total of 10 large square bales were formed and all were stored inside a typical open front hay shed. Sixteen net wrapped and eight twine wrapped round bales were formed. Half the net wrapped bales were stored inside the open front hay shed while the remaining net wrapped and all the twine wrapped round bales were stored outdoors. Half of each wrapped type was stored directly on the soil and the remaining bales were placed on a raised, well-drained surface. The rows of round bales were placed on a level surface in a line running north-south with the ends butted tightly together and no obstruction to shade the surfaces.

Bales were removed from storage on June 19th and 20th, 2003. Bales were weighed and bored for moisture samples using the same equipment described above. After the bale was weighed, the maximum width, height and bottom length in contact with the soil was measured on both sides of the bale. Round and square bales stored indoors were bored similar to that described above. 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 20-cm (8-in.), one from each side and two from the bottom of the bale. The two side and bottom moistures were averaged and defined as the rind and bottom moistures, respectively. Two additional bore samples, one from each side, were taken from a depth of 20 to 50-cm (8 to 20 in.) and average moisture defined as the core moisture. The overall volume adjusted bale moisture was calculated using these moistures and the bale dimensions explained above.

Results and Discussion

Yield and Field Drying Characteristics

Stover DM yield was greatest at the beginning of the study and declined almost linearly throughout the study (fig. 1). Stover yield was in decline because all four hybrids were past their physiological maturity (table 1). A common rule of thumb used when considering biomass feedstock potential from corn stover is that the mass of stover will be about equal to the mass of grain harvested (Smil, 1983). However, the data presented here show that this is true only for a short period early in the fall that is much earlier than the typical corn grain harvesting dates (fig. 1-3). On 10/17, the average stover DM yield at grain harvest (table 2) was about 9.3 Mg/ha (4.1 ton/ac) while average grain DM yield was 13.0 Mg/ha (5.8 ton/ac), providing a ratio of stover:grain dry mass of about 71%. The ratio of stover to total crop mass was hybrid dependent and ranged from 41 to 46% through the typical grain harvest dates (fig. 2).

Table 2. Dry matter yield of corn plant fractions at beginning and near the end of study period (average of Pioneer, Kaltenberg and Agri-Gold hybrids).

Fraction	Aug 28th		Oct 14th		Change
	Mg/ha	(ton/ac)	Mg/ha	(ton/ac)	%
Grain	7.23	3.23	13.08	5.84	80.8%
Cob	2.28	1.02	1.54	0.69	-32.6%
Husk	1.22	0.55	0.65	0.29	-46.5%
Leaf	2.89	1.29	1.53	0.68	-47.0%
Total stalk	5.59	2.50	5.56	2.48	-0.8%
Bottom stalk	2.52	1.13	2.52	1.13	0.0%
Mid-bottom stalk	1.99	0.89	2.08	0.93	4.5%
Mid-top stalk	0.80	0.36	0.74	0.33	-7.5%
Top stalk	0.28	0.13	0.22	0.10	-23.4%

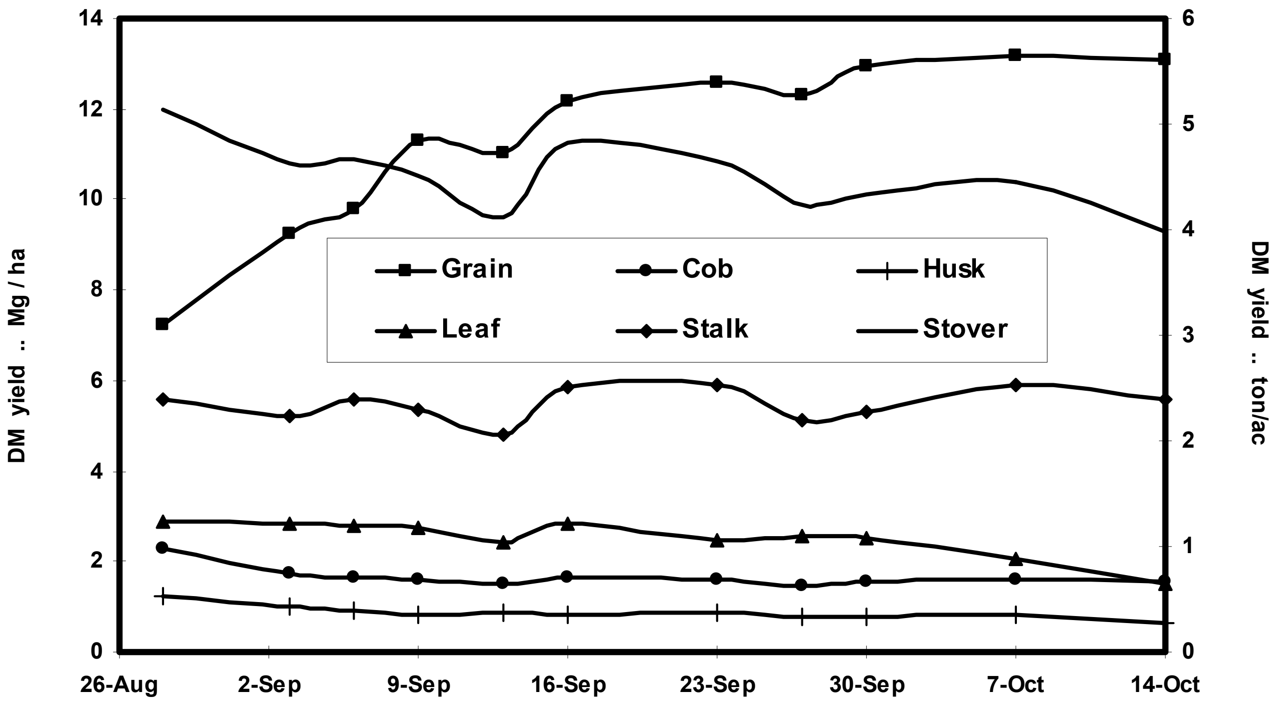

Figure 1. Dry matter yield of grain and stover fractions as fall progressed (average of Pioneer, Kaltenberg and Agri-Gold hybrids).

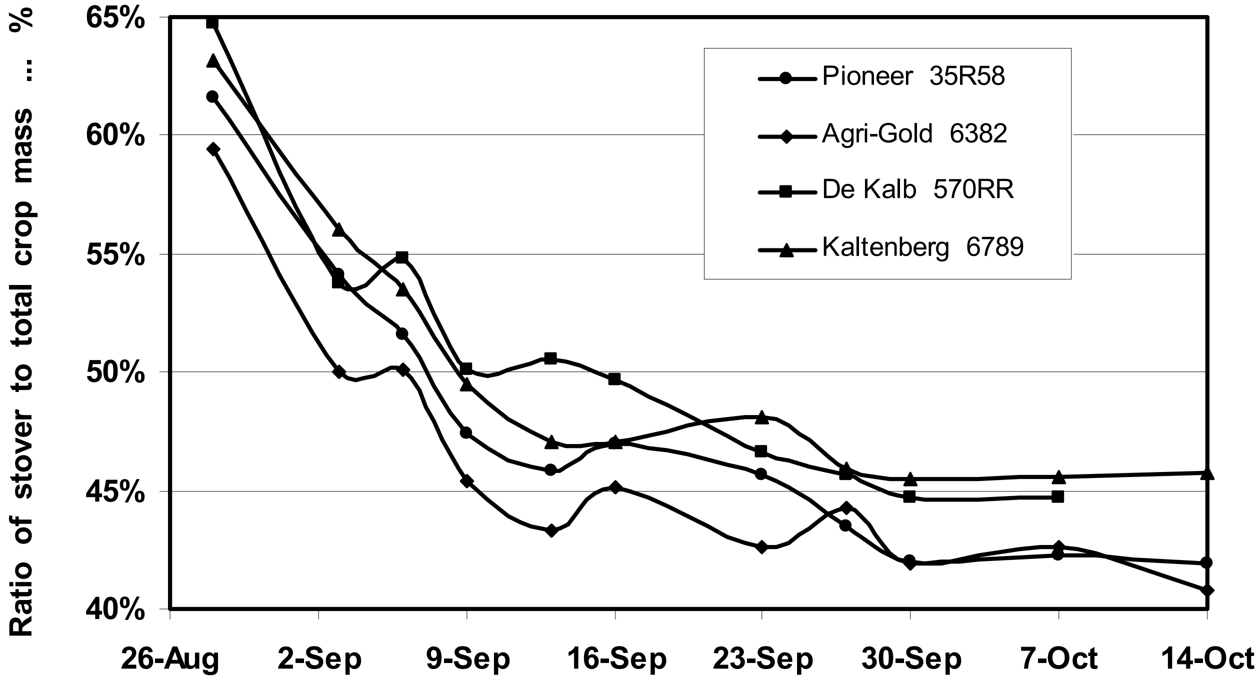

Figure 2. Ratio of dry stover mass to total crop dry mass for four different corn hybrids as fall progressed.

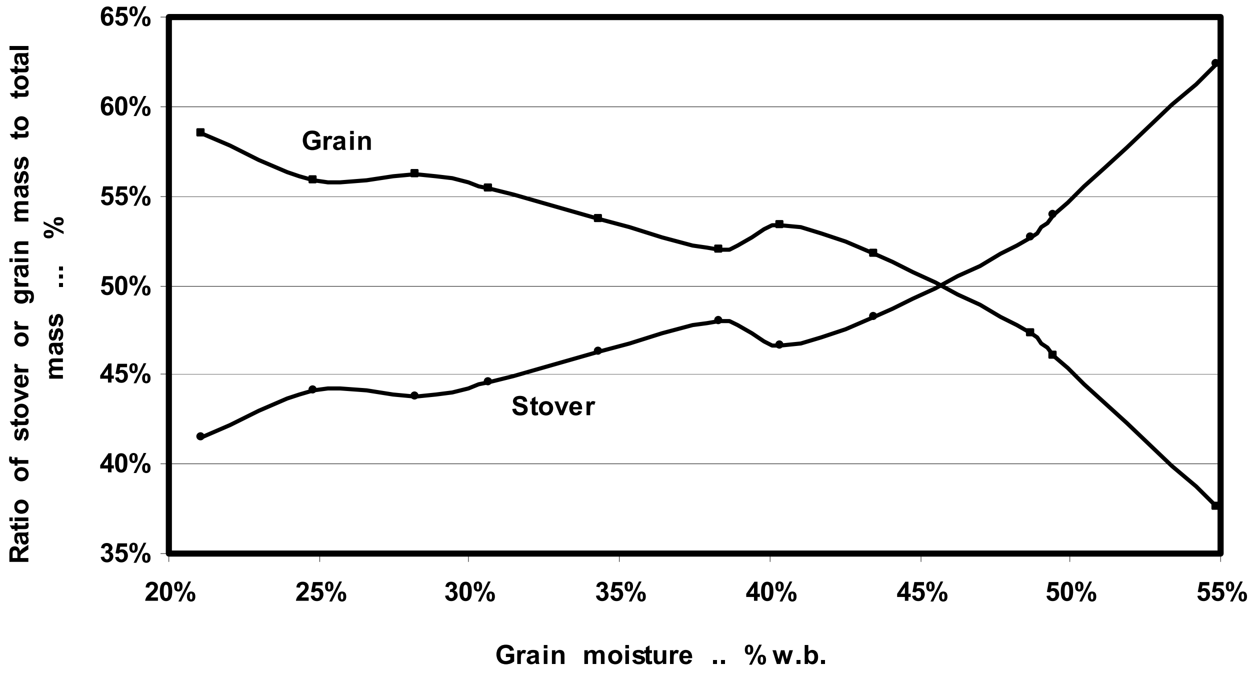

Figure 3. Ratio of stover or grain dry mass to total dry crop mass as a function of grain moisture (average of four hybrids).

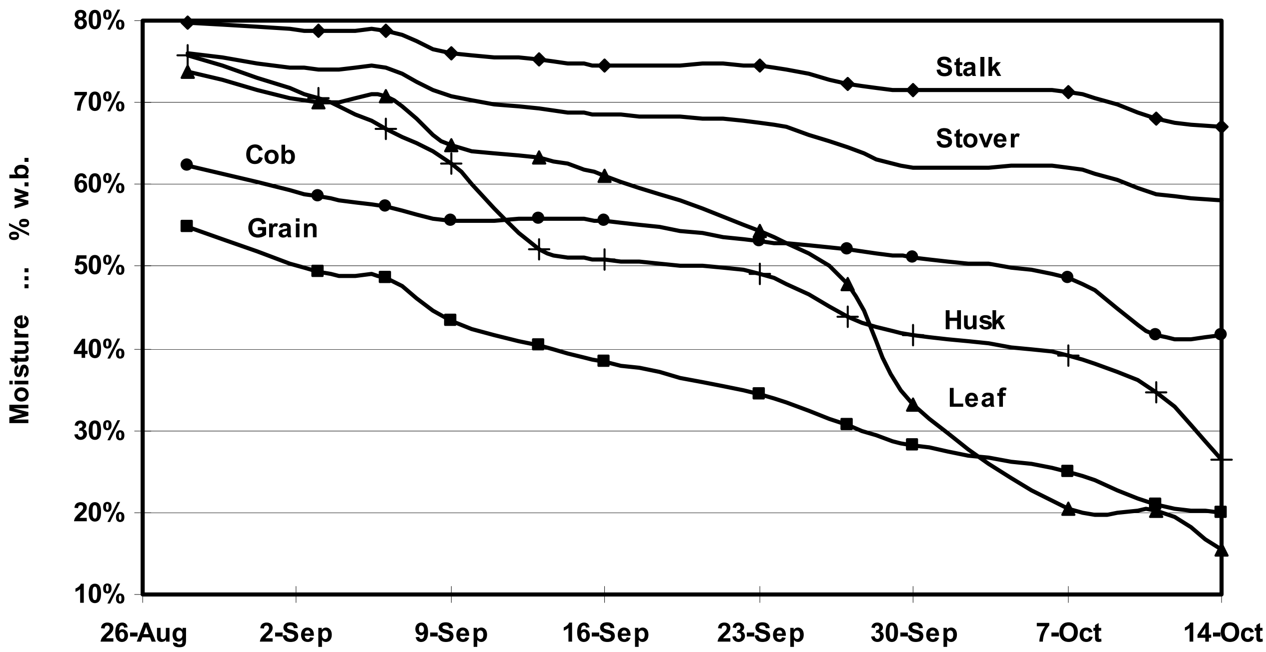

Figure 4. Moisture of corn plant fractions as the fall progressed (average of Pioneer, Kaltenberg and Agri-Gold hybrids).

Grain yield continued to increase until about two weeks before typical harvest date while stover yield declined almost linearly throughout the study period (fig. 1). The loss of stover mass occurred primarily because leaves and husk became brittle and were lost due to weathering (fig. 1, table 2). Dry matter loss in the cob was most likely due to respiration and microbiological activity. Stalk yield was only slightly lower over time as the top half of the stalk was lost as the plant weathered and deteriorated (fig. 1, table 2). These results are similar to those found by Pordesimo et al. (2002). Roughly 45 and 80% of the stalk DM is found in the bottom one-quarter and one-half of the stalk, respectively (table 2). If stover yield is to be maximized, harvesting systems must be developed that allow the bottom half of the stalk to be fully harvested. At the time of grain harvest, about 16, 7, 16 and 60% of the total stover dry mass resides in the cob, husk, leaf and stalk fractions, respectively (table 2).

The ratio of grain to total dry mass is important when estimates of stover potential yield are made based on grain yield. Research reported by Leask and Dynard (1973), Preston and Schwinn (1973), Lipinsky et al. (1977), Nielson (1995), Linden et al. (2000) and others indicated a grain mass fraction of 45 to 55% of total corn crop DM yield. These values would confirm the common rule of thumb of one unit mass of stover for a unit mass of grain. However, differences between harvesting method, stage of maturity, and harvest date have no doubt lead to much variation in this estimate. Our research shows that the ratio of grain dry mass to total mass increased from about 38% on 8/28 to about 59% on 10/16 (table 2). Therefore, the stover to total ratio declined from 62 to 41%. During the typical harvest period in the Upper Midwest when grain moisture is between 30 and 20%, the ratio of stover to total dry mass was less than 45% and averaged 43% (fig. 3). These results are similar to those found by Pordesimo et al. (2002).

Although there were some differences in moisture of the different hybrids, the data were pooled to provide a representative measure as the fall progressed. The decline of moisture over time was greatest for the grain, leaf and husk fractions while the stalk remained relatively wet (fig. 4). The leaf and husk lost moisture because of senescence, and their large surface area and thin cross-section. After the grain reached "black layer" maturity, it was essentially sealed off from the rest of the plant and lost moisture through evaporation to the atmosphere. The moisture content of the four stalk sections indicates that the bottom half of the stalk remained at high moisture throughout the fall harvest period (fig. 5). The rind of the stalk is physiologically structured to maintain the moisture in the plant as a drought defense mechanism and this makes it difficult for moisture to leave the plant in the fall. Until the plant is truly dead, some evapotranspiration continues to take place even as the grain dries, so water will continue to move into the stalk from the root structure. Some sort of mechanical conditioning is needed after grain harvest to split the stalk to allow an egress for the moisture trapped in the stalk pith. Even if only the top ¾ of the stalk were harvested, the moisture would be about 60% compared to the whole-stalk moisture of about 68%. The moisture of the stover fraction during the typical grain harvest moisture period (30 to 20%) ranged from about 65 to 58%. This was much higher moisture than that reported by Edens et al. (2002). In their work, stover moisture ranged from 60 to 40% during the same period the grain was 30 to 20%. Their work was conducted in Tennessee where ambient conditions would favor more rapid dry down of the stalk. The results here show the difficulty that will be faced in the Upper Midwest when stover is to be dried for harvest as dry material. Another common rule of thumb is that stover moisture is roughly twice that of the grain (Buchele, 1975; Nielson, 1995). This was only the case when the grain moisture was about 35% (fig. 6). The grain fraction lost moisture at a considerably faster rate then the stalk fraction so the overall stover:grain moisture ratio was much higher than 2:1 for most of the grain harvest period.

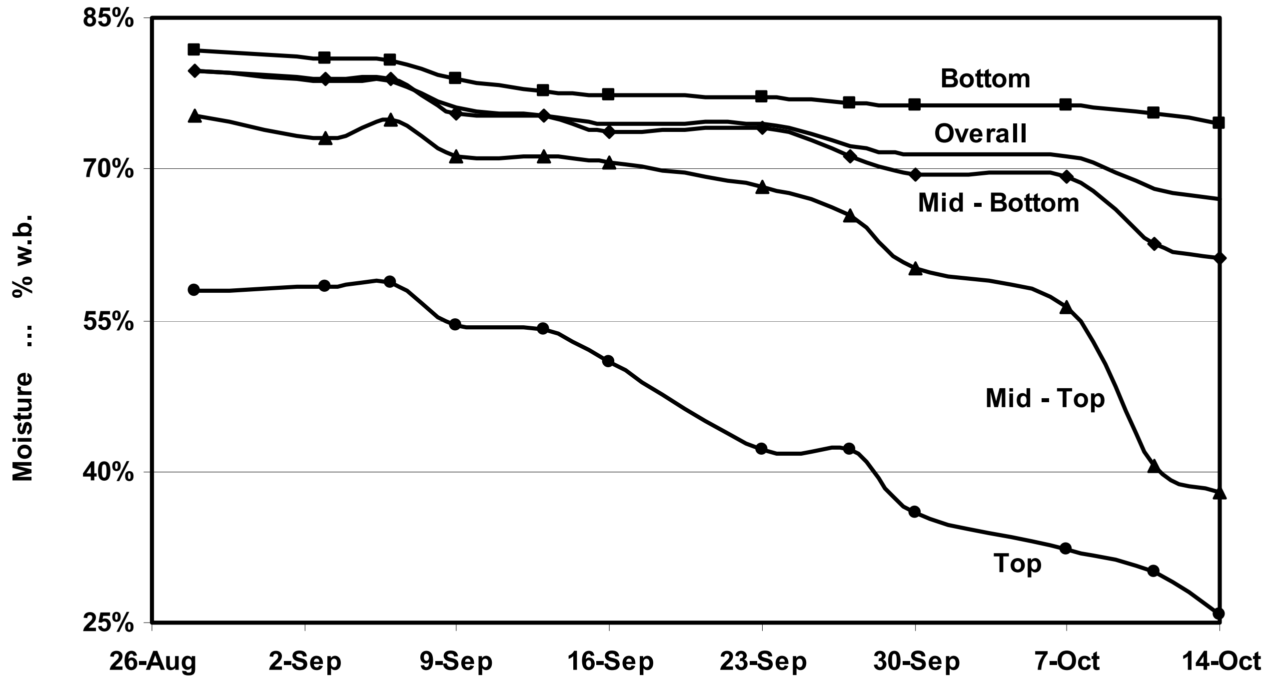

Figure 5. Moisture of various stalk fractions as the fall progressed (average of Pioneer, Kaltenberg and Agri-Gold hybrids).

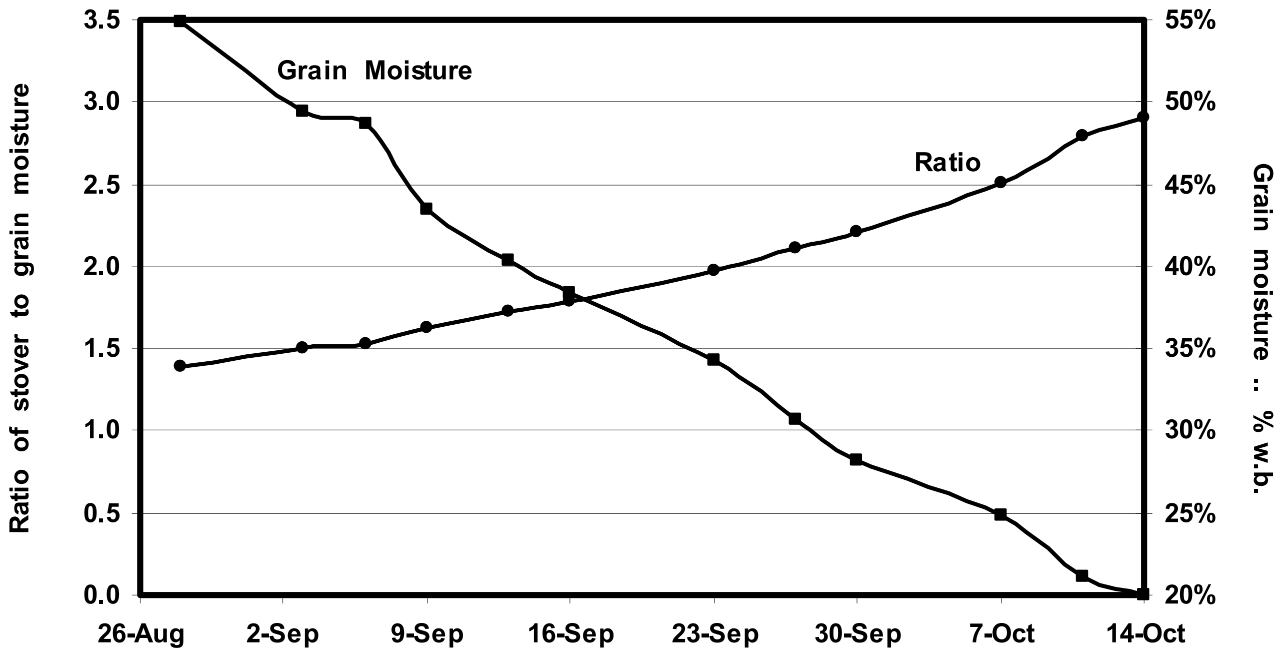

Figure 6. Ratio of stover to grain moisture as the fall progressed (average of Pioneer, Kaltenberg and Agri-Gold hybrids).

Stover Field Drying Characteristics After Harvesting

Field drying conditions were very challenging during the approximate three weeks after grain harvest. There were small rain showers on 8 of the 23 days and two more significant rain events on day 9 and 16 of the drying period. A total of 25-mm (1-in) of rain fell during the 23-day drying period. The average temperature during the drying study was 4.8ºC (40ºF). These were about average conditions for Madison, Wisconsin during mid to late October (40-mm or 1.6-in precipitation and 9ºC or 48ºF). Only during one brief period did the moisture of two of the treatments reach the low 20% moisture range acceptable for baling (fig. 7). In the second study, none of the treatments even approached the desired moisture range during the 10-day drying period (fig. 8). Mechanical conditioning in the form of flail shredding significantly improved the drying rate when the crop was placed in a wide swath behind the shredder (fig. 7 and 8). This was because the flail shredder worked well to split the stem open, allowing for the trapped moisture in the pith to escape more readily. Placing the shredded material in a narrow windrow at shredding is desirable because it could 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, windrowing at shredding significantly reduced the drying rate, in fact retarding it to the extent that the unconditioned control actually dried at a faster rate (figs. 7 and 8). The windrow density was such that air movement was probably restricted and the impact of the incoming solar radiation was minimized. When rain events occurred, the shredded treatments were more affected than the untreated treatments (figs. 7 and 8). 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 and allowed water to shed more easily. The 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 until there is an anticipated stretch of good weather might enhance the possibility of achieving the desired moisture range. Edens et al. (2002) reported that stover moisture was less than 20% within two weeks after grain harvest in Tennessee. The differences in results are most likely due the later harvest date and lower ambient air temperatures in Wisconsin.

Harvesting and Storing Wet Stover – Chopped and Bagged

Right before grain harvest, the moisture of the stover fraction of the standing plant was about 63% (w.b.). The stover fraction was shredded and windrowed within an hour or so of grain harvest and then allowed to sit in the field until late the next morning. The ambient conditions during that period were quite warm (11ºC (52ºF)) and very windy, so there was quite a bit of moisture loss in the stover despite the fact that the stover had been placed in a doubled windrow (12-m (40-ft.)) (table 3). This large reduction in moisture also might have been partially due to the make-up of the material actually harvested. For instance, if the material actually harvested consisted of a higher fraction of leaf and husk than would normally be available on the plant, then the stover moisture would have been skewed downward. The longest TLC was harvested last and had the lowest moisture of the treatments because of the rapid dry down that day (table 3).

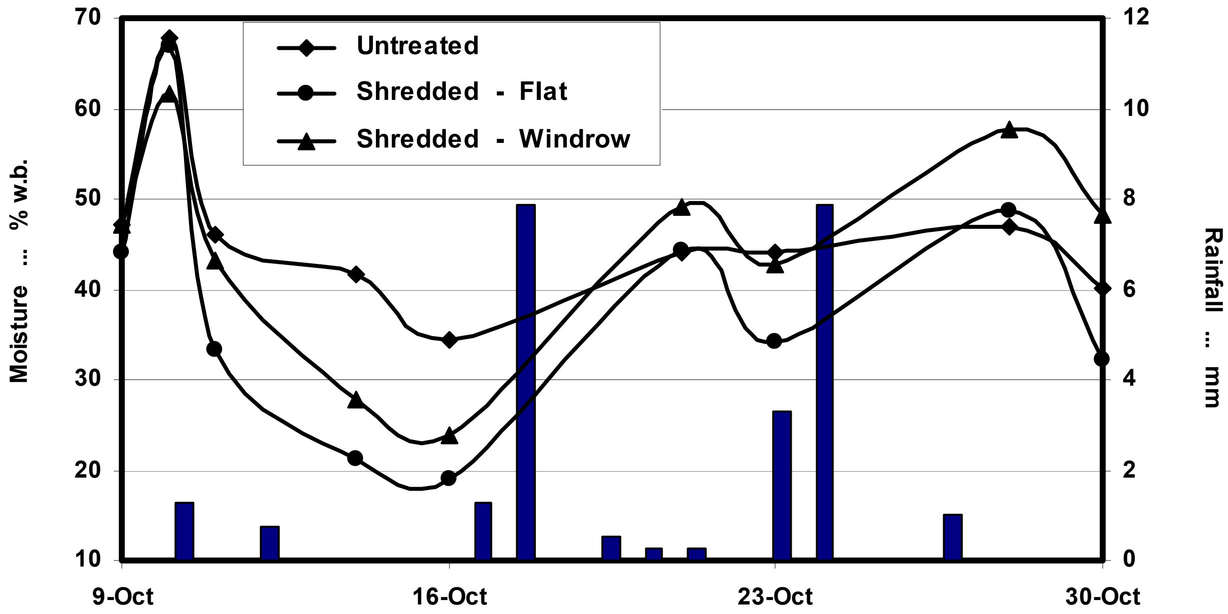

Figure 7. Drying rate of stover after grain harvest as affected by three conditioning treatments – 1st drying study (magnitude of rainfall events indicated by vertical bars).

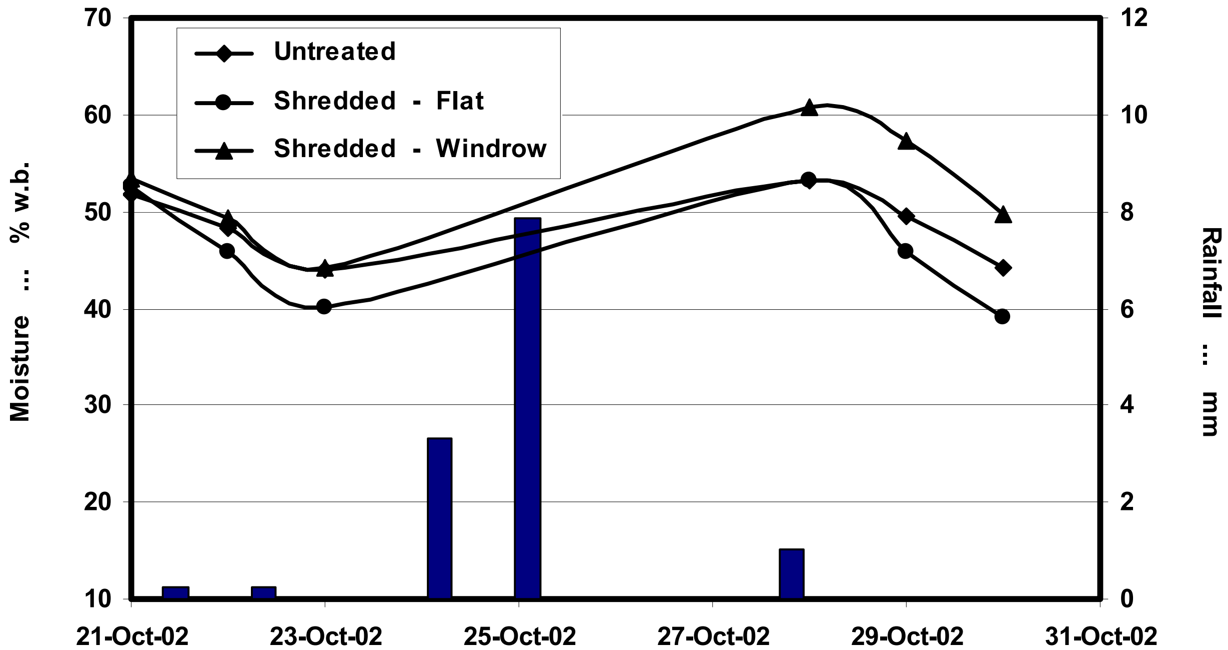

Figure 8. Drying rate of stover after grain harvest as affected by three conditioning treatments – 2nd drying study (magnitude of rainfall events indicated by vertical bar).

The windrow proved to be quite difficult to pick-up with the forage harvester's windrow pick-up crop unit, which is typically used for alfalfa and grasses. These crops are typically intertwined in the windrow and feed continuously into the pick-up and feedrolls. The shredded stover was not intertwined, so the pick-up teeth had difficulty gathering the material and often kicked it ahead rather than lifting and gathering it. The only way to overcome these difficulties was to slow forward speed to about 5.6 km/h (3.5 mi/h). Therefore, harvesting capacity was limited not by available power but by the inability to gather the stover with the windrow pick-up (table 3). The harvesting efficiency of shredding, windrowing and chopping was 53% (table 3, see footnote), meaning that just over half the available stover mass was actually collected. Shredding more than halved the particle-size of the stover (table 3). The ratio of actual particle-size to TLC decreased as TLC increased. Similar results were found by Savoie et al. (1989) with grass forages. The density of the material in the truck was negatively correlated to particle-size while there was no statistical difference in harvesting mass-flow-rate as affected by TLC (table 3).

Table 3. Productivity and physical properties of corn stover harvest as chopped material using precision-cut forage harvester and ensiled in plastic silo bag.[#]

TLC treatment	Moisture	Harvester mass-flow		Density in truck		Density in silo bag		Particle-size
		wet	dry	wet	dry	wet	dry	
SI Units	% w.b.	Mg/h		kg/m^3		kg/m^3		mm
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* (P = 0.05)	4.1	14.3	9.1	18	5	91	43	
English Units	% w.b.	ton/h		$lb./ft^3$		$lb./ft^3$		in.
0.25-in.	48.4	54.2	28.6	9.9_b	5.1_b	18.0	9.4	0.7
0.50-in.	47.9	59.3	30.9	8.4_a	4.3_a	18.8	9.8	1.0
0.75-in.	45.8	61.2	33.2	7.9_a	4.2_a	17.9	9.4	1.1
LSD* (P = 0.05)	4.1	15.8	10.0	1.1	0.3	5.7	2.7	

– Particle-size of stover before shredding and chopping was 690-mm (27-in.) and after shredding but before chopping was 290-mm (11.5-in.). Stover yield of standing plant material was 9.2 Mg DM/ha (4.1 ton DM/ac) just preceding grain harvest. Average harvested yield after shredding, windrowing and chopping was 4.9 Mg DM/ha (2.2 ton DM/ac).

* – Averages with different subscripts in the same column are significantly different at 95% confidence

Storing chopped wet stover in a bag silo was reasonably successful. The chopped material was removed from the bag after about 7 months of storage. The chopped stover had excellent appearance and color and had a familiar, pleasant ensiled odor. However, pockets of mold were observed frequently at the surface where the bag was not held tightly against the stover. Dry matter loss was 10.9% of total (table 4). 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 4.4 percentage unit rise in moisture during storage shows that some biological respiration did occur (table 4). Silage fermentation was quite good, with low pH and acceptable levels of lactic and acetic acid.

Several random grab samples of the stover were hand separated into the five plant fractions after storage and compared to the fractions found prior to and after grain harvest. The proportion of stalk in the stover was less after stover harvest because the flail shredder was set at a height that left about 15-cm (6-in.) of stalk standing (table 5). 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.

Table 4. Final storage data for chopped wet stover stored in a plastic bag silo in October 2002 and removed from storage June 2003.

Initial moisture % w.b.	Final moisture % w.b.	DM loss % of total	pH	Fermentation products % of DM			
				Lactic acid	Acetic acid	Butyric acid	Ethanol
47.3	51.7	10.9	4.1	3.66	1.01	0	0.26

<u>Table 5.</u> Fraction of total corn plant contained in each of the five parts prior to grain harvest, after grain harvest and after stover harvest.

	Standing crop prior to grain harvest	After grain harvest	After stover harvest
	Percent of total DM		
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

Harvesting and Storing Wet Stover – Baled and Wrapped

Right before grain harvest on 10/11, the moisture of the stover fraction of the standing plant was about 63% (w.b.). The stover fraction was shredded and windrowed within about an hour of grain harvest and then raked into double windrows within a few hours of shredding. The ambient conditions during that period was very warm (14ºC (58ºF)) and windy, so again there was quite a bit of moisture loss in the stover despite the fact that the stover had been placed in a doubled windrow (9-m (30-ft.)) (table 6). Again the moisture loss phenomenon might have been partially due to the make-up of the material actually harvested.

Table 6. Productivity and physical properties of wet corn stover harvest as baled material using large round or large square balers and ensiled in plastic film wrap.

Baler treatment	Moisture	Baler mass-flow		Bale density		Harvested yield[#]	
		wet	dry	wet	dry	wet	dry
SI Units	% w.b.	Mg/h		kg/m^3		Mg/ha	
LRB	37.9	18.0_a	11.2_a	176_a	109_a	6.7_a	4.3_a
LSB	39.9	34.7_b	20.9_b	248_b	149_b	9.0_b	5.4_b
LSD[*] (P = 0.05)	2.9	2.5	1.6	13	6	0.9	0.5
English Units	% w.b.	ton/h		$lb./ft^3$		ton/ac	
LRB	37.9	19.9_a	12.4_a	11.0_a	6.8_a	3.0_a	1.9_a
LSB	39.9	38.3_b	23.0_b	15.5_b	9.3_b	4.0_b	2.4_b
LSD[*] (P = 0.05)	2.9	2.8	1.8	0.8	0.4	0.4	0.2

– Stover yield of standing plant material was 8.6 Mg DM/ha (3.8 ton DM/ac) just preceding grain harvest.
* – Averages with different subscripts in the same column are significantly different at 95% confidence.

The rotary rake was very effective in producing a well-defined windrow for the balers. It also did a very good job of sweeping the field clean of the shredded stover, however it was also prone to raking in soil when field irregularities were encountered. The pick-up 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 rather by ground speed limitations at the pick-up. The stover yield of the standing plant material just preceding grain harvest was 8.6 Mg DM/ha (3.8 ton DM/ac). Therefore, the harvesting efficiency of shredding, raking and baling was 50 and 63% for the large round and large square balers, respectively. The pick-up for the large square baler was wider than that for the round baler by 46-cm (18-in.). Both pick-ups tended to push material to the side when gathering difficulties were experienced. When this occurred, the narrower pick-up of the round baler created higher losses that led to the lower harvesting efficiency.

The shape and handling characteristics of the bales was very good. Both bale types were easily moved with conventional lifting equipment and no difficulties were experienced when wrapping either bale type with plastic film. The large square bales of stover had 37% greater dry density than round bales. Shinners et al. (2002) reported densities of alfalfa at 35 to 45% moisture of 151 and 177 kg DM/m^3 (9.4 and 11.1 lb./ft^3) for large round and square bales, respectively, a 17% difference. The corn stover, even after shredding, had many large diameter, intact stalk sections that resisted the compression forces in either baler. Densities were therefore 28 to 16% 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 using either baler type.

The productivity of the large square baler was almost double that of the round baler. About 25% of the round baling time was spent at idle while wrapping with twine, which greatly reduced productivity. The square baler pick-up 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 (2.2 and 2.6 mi/h) for the large round and square balers, respectively.

Storing wet stover bales by wrapping and ensiling was quite successful. Bales were removed from the tube after about 7 months of storage. The bales had excellent appearance and color and had a familiar, pleasant ensiled odor. Mold was observed very infrequently, mainly at the ends of the bale. There were no statistical differences in DM loss between large square and round bales; however the large square bales had numerically higher DM loss (table 7). Shinners et al. (2002) reported that DM loss of alfalfa bales at 35 to 57% moisture wrapped in film tubes ranged from 2.2 to 6.8% with no trend over several trials for one bale type to have lower losses than the other. The average DM loss for ensiled stover bales of 3.6% was less than that found for dry stover bales stored indoors of 4.9% (table 8) and less than the average for wrapped alfalfa bales of 4.4% (Shinners et al., 2002). Losses of chopped forage stored in tower, bunk or bag silos have been reported to range from 5 to 20% dependent upon such management factors as moisture, packing density and feed-out rate (Pitt, 1990; Muck and Rotz, 1996; Muck and Holmes, 2000). Losses with wrapped bale high-moisture silage have been reported to be less than this, typically in the range of 3 to 12% (Huhnke et al., 1997; Shin, 1990; Kennedy, 1987).

Table 7. Final storage data for wet stover bales formed and wrapped in a tube of plastic film October 2002 and removed from storage June 2003.

	Initial moisture % w.b.	Final moisture % w.b.	DM loss % of total	pH	Fermentation products % of DM			
					Lactic acid	Acetic acid	Butyric acid	Ethanol
LRB	37.9	38.9	3.0	5.3	1.19	0.77	0	0.31
LSB	39.9	40.7	4.2	4.8	1.73	0.79	0	0.46
LSD* (P = 0.05)	2.9	3.7	2.7	0.8	0.82	0.14	-	0.25

* – Averages with different subscripts in the same column are significantly different at 95% confidence.

Fermentation products were lower and pH higher for the wrapped stover bales than would typically be expected of whole-plant corn silage (table 7). 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 lactic acids, respectively. 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 low-moisture stover can be very well preserved with limited fermentation as long as the plastic film limits oxygen. There were no statistical differences in fermentation products between bale types (table 7).

Shinners et al. (2002) reported that 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. 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.

Harvesting and Storing Dry Stover

Harvest of these bales took place almost six weeks after grain harvest. The stalks were shredded soon after grain harvest and were raked twice at two-week intervals and then again prior to baling in order to achieve the desired moisture. Although this many passes through the field would not be typical, it was required because of frequent rain or snow during the field drying period. The problems with poor gathering with the baler pick-ups were even more in evidence with the dry stalks, so baling speed was even more limited. Average ground speed during baling was 2.7 and 3.8 km/h (1.7 and 2.4 mi/h) for the large round and square balers, respectively. This was about 23 and 8% slower than the speed when baling wet stover for the large round and square balers, respectively. Slower speed only partially explains the drop in productivity from wet to dry stover (tables 6 and 8). Large round and square bales were 13 and 10% less dense, respectively, on a DM basis than wet stover bales (tables 6 and 8). The reduction in density also affects baling productivity for the round baler because baling must halt for wrapping when the volume of the bale chamber is full. More frequent stops reduced productivity because no baling occurred during wrapping. The reduction in bale density for both bale types might be due to the increased rigidity and strength of the drier stover providing more resistance to compression than the wet stover.

The harvesting efficiency of shredding, three rakings and baling was roughly 33 and 35% for the large round and large square balers, respectively, and was considerably lower than that for wet stover (see above). 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. Also, the dry stover was raked twice during the curing period. This probably increased losses and also provided some size-reduction that might have increased baler pick-up losses. The results suggest that yield and harvesting efficiency decrease as the delay between grain and stover harvest increases. Harvested yield was reduced 41% and harvesting efficiency fell from 57 to 33% when harvesting was delayed six weeks after grain harvest compared to 24-h wilting and wet-stover baling.

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 9). When this occurred, stover at the base of the bale mixed with the soil so that it could not be recovered when the bale was lifted. Material not recovered was considered part of the DM loss. When stored on pallets, it was observed that the bales wrapped with sisal twine had fewer tendencies to rot away and that some bales maintained their integrity throughout storage, decreasing DM loss compared to storing on soil (table 9). However, bales wrapped in sisal twine still had the highest DM loss of bales stored on pallets. Independent of storage method, net wrapped bales had about 62 and 31% 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 twine wrapped bales (tables 9), which 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 significantly lower moisture in the base of the bales. However, when stored on pallets, net wrapped bales still had 35% lower DM loss than twine wrapped bales. These results are very similar to those reported by Shinners et al. (2002) concerning bales of alfalfa or alfalfa/grass mixes.

Table 8. Productivity and physical properties of dry corn stover harvest as baled material using large round or large square balers and stored indoors and outdoors.

Baler treatment	Moisture	Baler mass-flow		Bale density		Harvested yield[#]	
		wet	dry	wet	dry	wet	dry
SI Units	% w.b.	Mg/h		kg/m^3		Mg/ha	
LRB – Twine	23.0	6.8_a	5.2_a	123_a	94_a	4.7_b	3.6_b
LRB – Net	23.5	7.3_a	5.5_a	138_b	106_b	2.9_a	2.2_a
LSB	24.0	17.2_b	13.1_b	178_c	134_c	4.3_b	3.1_b
LSD[*] (P = 0.05)	3.5	2.4	1.8	8	6	0.7	0.5
English Units	% w.b.	ton/h		$lb./ft^3$		ton/ac	
LRB – Twine	23.0	7.5_a	5.7_a	7.7_a	5.9_a	2.1_b	1.6_b
LRB – Net	23.5	8.0_a	6.1_a	8.6_b	6.6_b	1.3_a	1.0_a
LSB.	24.0	19.0_b	14.4_b	11.1_c	8.4_c	1.9_b	1.4_b
LSD[*] (P = 0.05)	3.5	2.6	2.0	0.5	0.4	0.3	0.2

– Stover yield of standing plant material was 8.9 Mg DM/ha (4.0 ton DM/ac) just preceding grain harvest. Stover was harvested about one month after grain harvest.

* – Averages with different subscripts in the same column are significantly different at 95% confidence.

Storing bales indoors significantly reduced DM loss compared to all other treatments (table 9). Average DM loss of large square and round bales stored inside was slightly less than 5% and there was no significant difference in losses between bale types (table 9). 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 round bales stored indoors was 45% less than the average DM loss of net wrapped bales stored outdoors.

Table 9. Storage characteristics of corn stover bales formed in November 2002 and removed from storage in June 2003[#].

	Moisture .. % wet basis					DM loss .. % of total
	Initial	Final				
		Rind	Core	Base	Volume adjusted total	
Stored inside						
Large round	25.9_{bc}				19.2_{a}	4.9_{a}
Large square	23.9_{ab}				19.3_{a}	4.8_{a}
Stored outside on ground[@]						
Sisal twine	32.0_{d}	46.8_{b}	20.4_{bc}	48.0_{c}	37.7_{d}	29.1_{e}
Plastic twine	24.4_{abc}	46.2_{b}	22.6_{c}	37.5_{bc}	36.4_{d}	14.3_{c}
Net wrap	22.2_{a}	35.8_{a}	18.9_{abc}	38.5_{c}	30.3_{c}	10.7_{bc}
Stored outside on pallets[@]						
Sisal twine	27.5_{c}	45.3_{b}	16.7_{ab}	28.3_{ab}	30.9_{c}	17.7_{d}
Plastic twine	23.0_{ab}	46.3_{b}	16.6_{a}	24.5_{a}	32.2_{c}	11.4_{c}
Net wrap	22.3_{a}	27.1_{a}	18.1_{ab}	24.2_{a}	23.5_{b}	7.0_{ab}
LSD[*] (P = 0.05)	3.5	9.3	3.7	11.2	3.3	4.3

– Total precipitation during storage period was 235-mm (9.3 in.).
@ – Only large round bales were stored outdoors.
* – Averages with different subscripts in the same column are significantly different at 95% confidence.

Conclusions

- When corn grain moisture was in the typical harvest range of 30 and 20%, the ratio of stover dry mass to total crop dry mass averaged 43%. At the time of grain harvest, grain and stover DM yields averaged 13.0 and 9.2 Mg/ha (5.4 and 4.1 ton/ac), respectively.

- At the time of grain harvest, on average about 16, 7, 16 and 60% of the total stover dry mass resides in the cob, husk, leaf and stalk fractions, respectively. Roughly 50% of the total stover dry mass was in the bottom half of the stalk. Stover yield decreased during the typical grain harvest period primarily because of losses in the leaf and husk fractions.

- The moisture in the total stover fraction was between 65 and 58% when grain moisture was in the typical harvest range of 30 and 20%. The leaf, cob and husk fractions dried considerably prior to grain harvest but the stalk remained over 65% moisture until grain harvest. The bottom quarter of the stalk remained above 75% moisture until harvest.

- Mechanically conditioning the stover by shredding after grain harvest significantly improved the stover drying rate if the material was placed back on the surface in a swath about as wide as the shredder width. Placing the shredded material into a narrow windrow immediately after shredding significantly reduced drying rate. No matter the treatment, in the three weeks after grain harvest only during a brief period was the stover at acceptable moisture for dry baling.

- Harvesting efficiency, i.e. the ratio of stover mass actually harvested to mass in the field, averaged 53, 56 and 33%, respectively, for chopping, wet baling and dry baling. Delaying baling for several weeks to achieve acceptable moisture for dry baling reduced harvesting efficiency because of biological activity and increased mechanical losses. Harvesting by shredding tended to leave proportionally more cob and stalk on the field.

- Harvesting wet stover as chopped material and ensiled in a plastic bag was successful. Harvester capacity was limited to an average of 28.0 Mg DM/h (25.4 ton DM/h) by difficulty in gathering shredded stover at the pick-up. Density in the truck and silo were negatively affected by longer length-of-cut. Dry matter loss of ensiled stover at 47% moisture was 10.9% of total after seven months of storage. The stover pH was 4.1, but there was evidence of mold growth at the surface.

- Harvesting wet stover as baled material and wrapping the bales for ensiling in a tube of stretch plastic film was successful. The large square baler produced greater harvesting rate, density and harvesting efficiency than the large round baler. Dry matter loss of tube wrapped bales at 40% moisture averaged 3.6% after seven months storage. Stover pH was 5.1. Bale color and odor were excellent with very little evidence of mold growth.

- Dry matter loss averaged 5 and 15% for bales stored indoors and outdoors, respectively. Average DM loss for bales stored outdoors was 8.9, 13.3 and 23.4% for bales wrapped with net wrap, plastic twine and sisal twine, respectively. Net wrapped bales had significantly lower moisture when removed from storage than twine wrapped bales. Independent of wrap type, average DM loss bales stored outdoors was 18.0 and 12.0% for bales stored on the ground and on a well drained surface, respectively.

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