Density profile of corn silage in bunker silos

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D'Amours, L. and Savoie, P. 2005. **Density profile of corn silage in bunker silos**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **47**: 2.21-2.28. Six commercial bunker silos were monitored at filling and packing during corn silage harvest. The silos were core sampled at two dates in the following months according to a pattern of 24 holes at six lateral positions and four heights and at two depths in each hole. The dry matter density of individual corn silage samples ranged from 115 to 361 kg DM/m³ (average 234 kg DM/m³). Samples taken in-depth (180 to 360 mm from the vertical face) were always denser than samples taken at the surface (0 to 180 mm from face) by an average of 9%. Samples taken near the top of the silo were always less dense than samples taken near the floor by an average of 23%. Samples taken at the centre were generally denser (11 cases out of 12) than samples taken near the wall by an average of 7%. The pattern of 24 holes cored at two depths illustrated variation according to sampling position and provided a good average density of a bunker cross-section. The in-depth density was considered more representative of stored density than the surface density which was reduced by feed removal operations. The average in-depth density at the six sites was highly correlated with grain percentage and silage height ($R^2 = 0.945$). A linear regression model predicted very well the experimental average in-depth densities which ranged from 196 to 293 kg DM/m³ while grain percentage ranged from 17 to 50% and silage height from 2.4 to 3.3 m. In the present study, the percentage of grain at harvest was the single most important factor to increase average dry matter density in bunker silos. **Keywords:** corn, silage, density, grain, storage, compaction, bunker silo, modeling.

Six fermes commerciales ont fait l'objet d'un suivi lors du remplissage et du compactage de maïs ensilage dans des silos couloir. Quelques mois après le remplissage, chaque silo a été échantillonné à deux dates selon une grille de 24 trous à six positions latérales et quatre hauteurs, et à deux profondeurs par trou. La masse volumique d'échantillons individuels a varié de 115 à 361 kg de matière sèche (MS)/m³ (moyenne de 234 kg MS/m³). Les échantillons en profondeur (180 à 360 mm de la face verticale) étaient toujours plus denses que les échantillons en surface (0 à 180 mm de la face), de 9% en moyenne. Les échantillons près du sommet étaient toujours moins denses que les échantillons près du plancher, de 23% en moyenne. Les échantillons au centre étaient généralement plus denses (11 fois sur 12) que les échantillons près du mur, de 7% en moyenne. La grille de 24 trous échantillonnés à deux profondeurs a mis en évidence la variation selon la position et a fourni une bonne moyenne de la masse volumique d'une section verticale d'un silo couloir. La masse volumique en profondeur était considérée plus représentative que la masse volumique en surface réduite par les opérations de reprise. La moyenne de la masse volumique en profondeur était hautement corrélée avec le pourcentage de grain et la hauteur de l'ensilage ($R^2 = 0{,}945$). Un modèle de régression linéaire prédisait très bien la masse volumique moyenne en profondeur qui a varié entre 196 et 293 kg MS/m³ pour un pourcentage de grain entre 17 et 50% et une hauteur d'ensilage entre 2,4 et 3,3 m. La présente étude a montré que le pourcentage de grain était le facteur le plus important pour augmenter la masse volumique du maïs dans les silos couloir. **Mots-clés:** maïs, ensilage, densité, entreposage, compactage, silo couloir, modélisation.

INTRODUCTION

Density of corn silage is highly variable in bunker silos. Muck and Holmes (2000) reported values in the range of 125 to 378 kg DM/m³ for corn silage sampled from 81 commercial bunker silos in Wisconsin. The average was 232 kg DM/m³. A high density is desirable because more dry matter is stored in the same volume and the fixed costs of storage per unit dry matter are reduced.

Density is also linked to forage quality and preservation. Ruppel et al. (1995) observed that loss during storage was inversely proportional to density. Their model indicated that, over a six-month storage period, dry matter loss decreased from 20 to 10% when density increased from 160 to 320 kg DM/m³. A high density limits air infiltration and reduces oxidation loss during storage and retrieval.

Previous studies have correlated silage density in bunker silos with several factors, notably moisture content of the silage, mass of the compaction tractor, wheel pressure, time of compaction, silage height, layer thickness, and number of layers. Nine prediction models for silage density in bunker silos were reviewed by Savoie et al. (2004). Significant variables in each model tended to reflect the experimental emphasis: moisture content was important under a wide range of moisture, tractor mass was important when heavy tractors were used in contrast with light tractors, and layer thickness was important under a wide range of layer thicknesses. In a laboratory study simulating bunker silo compaction, Muck et al. (2004) found that the average dry matter density of alfalfa and grass was significantly affected by pressure, moisture content, crop species, and chop length, but not by layer thickness or time of compaction. In another laboratory study, Savoie et al. (2004) found that the average dry matter density of corn silage was significantly affected by layer thickness, crop processing, and pressure but not by time of compaction or moisture content. In both laboratory studies, dry matter density increased logarithmically with the number of layers.

Part of the difficulty in predicting silage density in bunker silos is the intrinsic variation of density within a silo. Muck and Huhnke (1995) observed that density increased from top to bottom of bunker silos, probably due to a combination of self-compaction under silage weight and cumulative compression from the packing tractor. Silage density was also expected to decrease on the vertical face during feeding because of unloading equipment perturbations. Silage density may also vary laterally, especially near the sidewalls when the spreading loader is wider than the wheel base or when the packing tractor is close to the top of the wall and the operator purposely reduces the number of passages for safety reasons.

Table 1. Description of commercial dairy farms and bunker silos which were monitored for corn silage storage.

Site #	Region	Number of cows	Yearly milk production (kg/cow)	Corn silage area (ha)	Silo size		
					Width (m)	Length (m)	Height (m)
1	Nicolet	40	8000	10	4.9	21.3	3/05
2	Beauce	230	9800	7	12.2	46.0	3.66
3	Beauce	200	8400	50	15.2	46.0	3.66
4	Beauce	70	9000	13	4.6	28.7	2.44
5	Nicolet	180	8000	32	11.0	52.4	2.44
6	Nicolet	70	8500	13	9.1	39.6	3.05

The main objective of this research was to characterize the density profile of corn silage in bunker silos. Factors that were considered included the mass of the compaction tractor, tire size and air pressure, time of compaction, time of spreading, harvest rate, and crop characteristics (chop length, moisture content, percentage of grain). To obtain representative data in a variety of conditions, six commercial farms were selected. A method to adequately measure the density profile in a bunker silo was developed.

MATERIAL and METHODS

Site selection

Six dairy farms were selected to represent a variety of bunker silo sizes and two climatic zones with a difference of about 400 crop heat units (CHU) according to geographic maps for eastern Canada (Bootsma 1999). Three silos were located in the Beauce region in the province of Québec (agricultural region of Chaudière-Appalaches, about 2200 CHU) and three other silos were located in the Nicolet region (agricultural region of centre of Québec, about 2600 CHU). Table 1 describes the number of milking cows, milk production average, corn silage area, and the size of the specific bunker silo monitored on each farm. The size of the smallest silo was 4.9 m wide by 21.3 m long by 3.05 m high (theoretical volume of 318 m^3) while the size of the largest silo was 15.2 m wide by 46.0 m long by 3.66 m high (theoretical volume of 2560 m^3, which is 8 times the volume of the smallest silo).

Five out of six silos had a concrete backwall. The bunker silo at site #6 had only two side walls and no backwall. Moreover, the silo at site #6 was partially filled with perennial grass and legume forage (about 1 m deep over the entire length) prior to top-filling with corn silage. The five other bunker silos were filled with corn silage only.

Bunker silo filling operation

Corn silage harvest and bunker filling operations at the six sites occurred between September 26 and October 11, 2003. Each site was monitored for at least three hours per day of harvest. The empty mass and the full mass of forage wagons were measured with a dynamic low-speed-weighing-in-motion scale (± 25 kg, Mikros System Ltd, Pretoria, South Africa). The harvest capacity was averaged by counting the number of loads per hour. Each packing tractor was weighed; tire size and air pressure were also measured. The time to spread silage across the bunker (spreading time) and the time to run over the silage without spreading (compaction time) were measured separately, typically during a one-hour observation period per day of harvest.

Measured variables at filling

The density of chopped silage prior to mechanical compaction was measured in three buckets with the shape of a truncated cone of three different heights (0.15, 0.30, and 0.45 m) and volumes (9.5, 20.7, and 33.2 L). The inside diameter of all buckets at the bottom was 280 mm; the inside diameters at the top were 297, 313, and 330 mm, respectively. Each bucket was slightly overfilled manually, without compression, with loose freshly chopped forage and brushed horizontally at the top to reach the exact height of 0.15, 0.30, or 0.45 m. Each bucket was filled three times during a day of harvesting. After weighing each bucket, a sample of about 250 g was conserved for oven-drying during 24 h at 103ºC to estimate moisture content (standard S358.2, ASAE 2002a). Density was always reported on a dry matter basis (net forage dry mass divided by volume).

On each day of harvest, three other samples of about 2.5 kg of forage were conserved to measure chopped particle length by sieving. Mean particle length was determined and expressed according to standard method S424.1 (ASAE 2002b).

The percentage of grain in the chopped corn at harvest was determined by a hydrodynamic separation method slightly modified from the method described by Savoie et al. (2003). Fresh samples of chopped corn were initially oven-dried to know the exact original dry matter (about 80 to 100 g DM per sample). The whole sample was mixed for 60 s in 7 L of water for the first separation. The material that had sunk during the first separation was relatively pure grain which was placed in bag #1 for oven drying. The floating and suspended material was mostly stover but also included some residual grains. A second water separation with the floating and suspended material resulted in more particles that sank which represented a mix of grain and stover. This mixed material was placed in bag #2 for oven drying. The floating and suspended material after the second separation was relatively pure stover and placed in bag #3 for oven drying. The three bags were oven-dried at 103°C for 24 h. After oven-drying, bag #2 was manually separated into grain and stover. The total non-dissolved grain and total non-dissolved stover were added. The quantity of dissolved dry matter was estimated by subtraction from the original total dry matter. Typically, dissolved dry matter represented 10% of original dry matter. Based on results of Savoie et al. (2003), half the dissolved dry matter was attributed to grain and the other half was attributed to stover. Hence, the total fraction of grain could be estimated.

Measured variables at feeding

The density of chopped silage after compaction and fermentation was measured by taking horizontal core samples at the bunker face at 24 positions and two depths at a given date and a given site. Each site was visited between November 17 and December 16, 2003 for the first sampling and between January 13 and February 24, 2004 for the second sampling. A

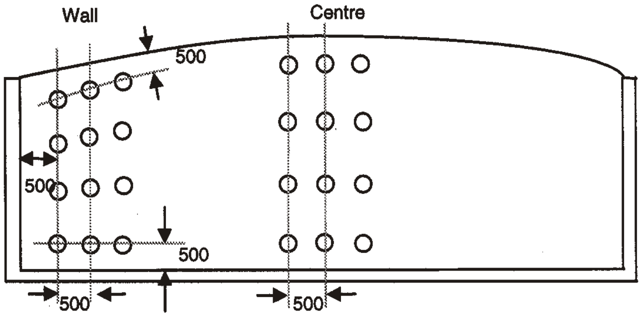

Fig. 1. **Core sampling pattern to determine the silage density profile (distances in mm). A total of 48 samples were taken at each site and each date from the 24 holes illustrated at two depths: 0 to 180 mm from the face and 180 to 360 mm from the face.**

third sampling in May 2004 was done to obtain validation data. Only data from the first two samplings were used for statistical analysis and the development of a prediction model.

To characterize the silage density profile, three position factors were chosen: the height at four levels, the lateral position (near the centre or near the wall), and the depth (at the face or at a fixed horizontal distance behind the face). Three replications corresponded to three vertical lines at each lateral position. Figure 1 illustrates the 24 positions of core sampling. A total of 48 samples were obtained from the 24 holes at two depths, at the face (0 to 180 mm deep) and in depth (180 to 360 mm from the face).

The four heights were taken as follows: 0.5 m from the floor, 0.5 m from the top of the silage, and at two intermediate heights. Intermediate 1 was closer to the floor and Intermediate 2 was closer to the top. The distance between two vertically adjacent sampling holes was approximately equal to the total height minus 1 m divided by three.

Core samples were taken with a manual auger of 73 mm diameter and a length of 180 mm (Figure 2). An elongated handle allowed to take a second sample in each hole to a depth of 360 mm. The wet mass of each core sample was weighed on site and the associated volume determined by the auger diameter and the real depth of each hole obtained with a measuring tape after the sample had been removed. Prior to coring each of the 24 holes, a small amount of forage was brushed off or shoveled away, especially for lower samples, to remove freshly tumbled silage and start sampling in the harder and more intact face.

Each of the 48 samples was divided in two parts: a larger part (typically 200 to 300 g wet) used to determine the moisture content and a smaller part (about 50 g) to determine pH and other chemical constituents not reported in the present paper. The moisture content was obtained by placing the forage in an oven for 24 h at 103ºC (Standard S358.2, ASAE 2002a).

The silage height was measured at six points along the width of a silo. The shape of the silage face was also measured to obtain an average distance along the lateral walls. Between the two dates of observation at each site, the average distance of silage retrieval was estimated from these measures. The average distance was used to estimate the retrieval or unloading rate.

Statistical analysis

The statistical utilities of Excel software were used to analyze the data for dry matter density. An analysis of variance was done on density prior to compaction based on two factors (thickness and site). The density prior to compaction was also analyzed by linear regression as a function of the measured variables at harvest (percentage of grain, mean particle length, moisture content) and step-wise deletion of non-significant variables ($p > 0.05$).

An analysis of variance was done on density after compaction and fermentation for each position factor (depth at the face, height, and lateral position) by a one-factor analysis with three replications while considering the other factors as blocks for each site and date of sampling. The average in-depth density for each site and date was analyzed by step-wise deletion using a linear regression model. The independent variables considered were percentage of grain, mean particle length, moisture content, silage height, and a packing factor (defined later as a function of tractor mass, harvest rate, and fraction of time dedicated to compacting).

RESULTS and DISCUSSION

Filling and packing bunker silos

The main parameters recorded during the filling and packing of bunker silos are presented in Table 2. When comparing values

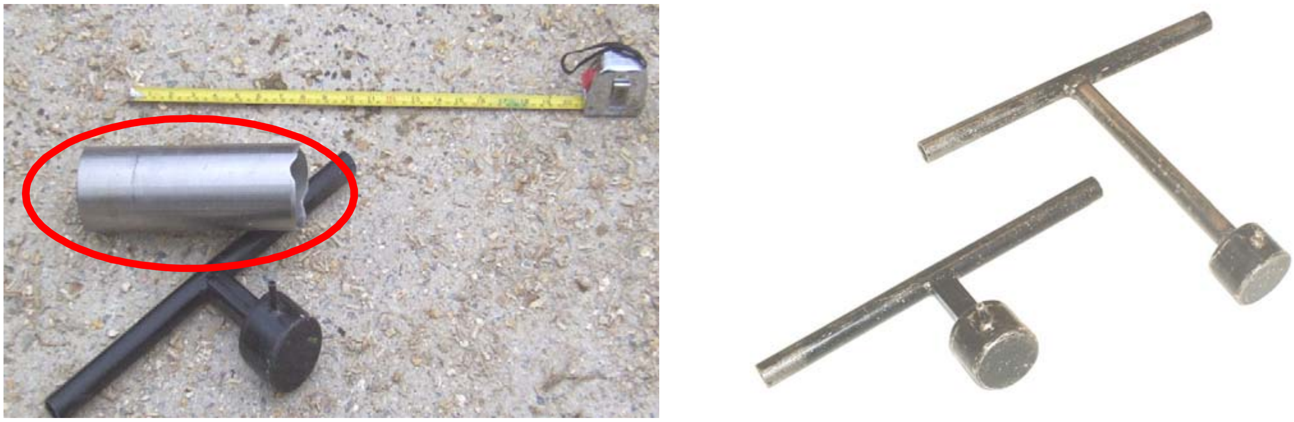

Fig. 2. **Core sampler of 73 mm diameter (circled) used with a standard handle for 0 - 180 mm depth or an elongated handle for 180 - 360 mm depth.**

Table 2. Average data gathered during bunker silo filling and at feeding (two sampling dates).

Site identification	1		2	3	4	5	6	
Harvest dates (2003)	Sept 30		Oct 11	Oct 7, 8, 10	Oct 8	Sept 26	Oct 9	
Moisture content (%)	61.8		67.5	71.0	76.8	61.9	55.8	
Mean chop length (mm)	9.8		14.4	10.5	9.5	12.7	8.3	
Percentage of grain (%)	49.5		28.2	25.9	17.0	41.0	41.1	
Wagon loads per hour	10.2		2.9	4.6	3.5	6.6	8.3	
Harvest capacity (t DM/h)	22.0		6.8	12.9	5.1	14.2	11.9	
Number of compaction tractors	2		1	1	1	1	2	
Tractor mass (kg)	7060	5760	9980	8520	5630	6500	6770	3610
Front tire size	16.9x28	13.6x28	16.9x30	14.9x28	13.6x24	14.9x28	14.9x24	14.9x24
Rear tire size	18.4x42	18.4x38	20.8x42	18.4x38	16.9x34	18.4x38	18.4x38	18.4x34
Tire pressure front/rear (kPa)	172/90	131/90	221/175	241/152	172/131	248/159	159/100	103/138
Spreading time (min:s/load)	03:22	00:51	04:58	08:33	08:31	01:42	01:00	00:00
Compaction time (min:s/load)	01:30	04:56	13:36	03:26	05:25	06:49	06:14	06:53
Packing time fraction	0.905		0.897	0.919	0.813	0.937	0.976	
Packing fraction (t h/t DM)	0.528		1.317	0.607	0.897	0.429	0.852	
Unloading equipment	Rotary cutter		Loader	Loader	Loader	Rotary cutter	Silo-grab	
Silage height on 1st date (m)	2.89		2.43	2.56	2.58	2.69	2.56	
Silage height on 2nd date (m)	3.13		3.29	3.26	2.73	2.85	2.75	
Retrieval rate (mm/d)	97		144	126	117	153	147	

from the six farms, the average harvest rate varied from 5 to 22 t DM/h, while the average moisture content ranged between 56 and 77%. The mean particle length of the chopped corn varied from 8 to 14 mm. The percentage of grain in the whole crop at harvest varied from 17 to 50%.

For packing, four farms used a single tractor while two farms (sites #1 and 6) used two tractors. The mass of the compaction tractors varied between 3.6 and 10 t. The tire pressure observed varied between 90 and 250 kPa. Wagons used to transport chopped forage from the field were either unloaded directly within the silo walls or on a slab just outside the silo. In either case, there was always an initial spreading time usually followed by a compaction time without spreading. The average time (min:s) per packing tractor to spread the silage varied from 0:00 to 8:33 per load while the compaction time varied from 1:30 to 13:36 per load. Total time to spread and compact varied between 4:52 and 18:34 per load for the six sites. These data were used to estimate the fraction of time spent packing silage over the total harvest time as:

$$f_{pt} = \left(t_s + t_c\right) / t_h \qquad (1)$$

where:

f_{pt} = packing time fraction,
t_s = spreading time,
t_c = compaction time, and
t_h = harvest time per load.

Harvest time per load is the inverse of the number of loads per unit time. Table 2 shows that the packing time fraction ranged from 0.81 to 0.98. The difference with respect to 1.00 is the fraction of time the packing tractor was idling or devoted to other chores besides spreading and compacting. When two tractors were used, f_{pt} was based on the average.

An overall packing factor was estimated as the total tractor mass multiplied by the packing time per load and divided by the dry matter per load. Such a packing factor may be calculated as:

$$PF = \left(m_T f_{pt}\right) / R_h \qquad (2)$$

where:

PF = packing factor (t-h/t DM),
m_T = tractor mass (t), and
R_h = harvest rate (t DM/h).

Table 2 shows that the packing factor ranged from 0.43 to 1.32 t-h/t DM. When two tractors were used, PF was based on total mass. The packing factor was used in the regression analysis described later to predict average compacted density.

Density prior to mechanical compaction

During the harvest period, 75 samples were taken to estimate the density prior to compaction of freshly chopped corn placed without compression in buckets of three different depths (0.15, 0.30, or 0.45 m) at the six sites. The individual values of density prior to compaction ranged from 42 to 119 kg DM/m³. There was no significant difference ($p = 0.74$) between the three buckets of different depths: the average densities were 72, 74, and 76 kg DM/m³ for the three depths of 0.15, 0.30, and 0.45 m, respectively.

However, there was a significant difference ($p < 0.001$) in density prior to compaction between sites with average values of 103, 57, 76, 60, 84, and 98 kg DM/m³ at the six sites, respectively. These differences could largely be explained by the mean particle length ($p = 0.016$) and percentage of grain ($p = 0.003$) in the chopped corn at harvest. Moisture content was not statistically significant ($p = 0.955$) when the two other variables were considered. Equation 3 predicts density prior to compaction for chopped corn with a coefficient of determination, R^2 of 0.976.

$$\rho_{ptc} = 75.6 + 1.34\% Grain - 3.79\, MPL \qquad (3)$$

where:

ρ_{ptc} = density prior to compaction for corn (kg DM/m³),

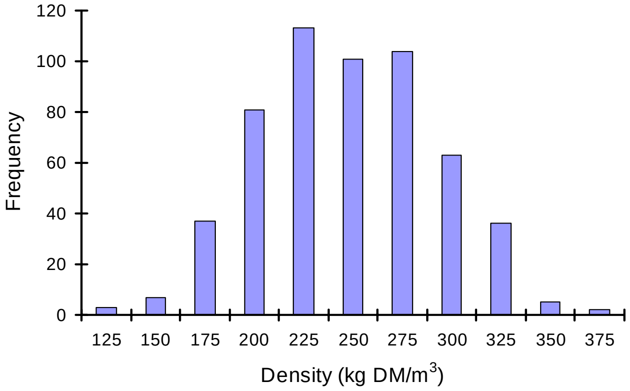

Fig. 3. Distribution of dry matter density of individual corn silage samples taken at two different dates from six bunker silos (total of 552 samples, average of 234 kg DM/ m^3).

MPL = mean particle length (mm), and
%Grain = percentage of grain (%).

Compacted density of corn silage

After mechanical compaction and a storage period between 2 and 5 months, 576 core samples of silage were taken at the six sites and two dates (48 samples per site and per date). Because one quarter of the samples at site #6 was actually hay crop under the corn silage, the 24 hay samples were excluded from the analysis. The moisture content of the remaining 552 corn silage samples ranged from 52.9 to 81.6% with an average of 66.1%. The compacted density of these samples ranged from 115 to 361 kg DM/m^3, with an average of 234 kg DM/m^3 (Figure 3). The density distribution was analyzed as a function of the three position factors: depth from the vertical silo face, height, and lateral position, i.e. centre versus near the wall. The analysis was carried out for the six individual sites and two dates of sampling at each site.

Density as a function of depth at the face. Results in Table 3 show that the dry matter density at the vertical surface of the bunker (0 to 180 mm from the face) was always lower than the density deeper in the silo (180 to 360 mm from the face). Moreover, the difference was statistically significant 6 times out of 12. On average, the density was reduced by 9% at the surface compared to the density in depth, at both dates of sampling. The density reduction varied between sites and dates, ranging from 4 to 16%. These differences could result from variations in unloading equipment and methods of removing silage from the bunker face.

A rough face or a tumbled face would normally have a relatively lower density. There was however no obvious relationship between the unloading equipment and the relative reduction in density due to retrieval. Sites #1 and 5 used a rotary cutter which normally leaves a smoother face than front end loaders used at sites #2, 3, and 4. Site #5 had the smallest variation of density at the face at date 1 but not at date 2. Face perturbation depends both on equipment and the way it is operated.

Because the in-depth density was always higher than the surface density, the former was considered to be more representative of density in the entire silo prior to unloading. For this reason, only the in-depth densities sampled between 180 and 360 mm from the vertical face were used to compare the other position factors (height and lateral position).

Density as a function of height. Table 4 indicates that density for the six sites was always lowest at 0.5 m from the top, i.e. at position H_4, where it averaged 222 kg DM/m^3 over the two dates. Density gradually increased as silage height increased up to the point H_1 located at 0.5 m from the floor where density averaged 267 kg DM/m^3 over the two dates. The average height of silage was 2.8 m over the six sites and two dates (Table 2). On average for the six sites, the dry matter density increased 9% between H_4 and H_3 (0.6 m lower), 15% between H_4 and H_2 (1.2 m lower), and 23% between H_4 and H_1 (1.8 m lower). The analysis of variance comparing density at the four heights indicated statistical differences 10 times out of 12 ($p < 0.05$).

In all cases, density near the top of the silo at H_4 was the lowest while density near the bottom floor at H_1 was the highest. In some cases, intermediate densities at H_3 and H_2 did not follow the expected pattern of density increase with increasing silage height above the sampling point. However, the overall average density over the six sites followed a definite trend of increasing density with increasing silage height (Table 4, average densities). The non-linear variation in intermediate

Table 3. Silage density (kg DM/m^3) at the vertical surface (0 -180 mm from the face) and in depth (180 - 360 mm from the face) for six sites and two dates. Average of 24 samples per density value except site #6 with 18 samples.

Site #	Date 1				Date 2			
	Surface	Depth	Difference (%)	Probability* (%)	Surface	Depth	Difference (%)	Probability (%)
1	253	288	12.2	0.002	254	293	13.3	<0.001
2	201	213	5.6	0.31	231	241	4.1	0.36
3	189	224	15.6	0.002	219	233	6.0	0.09
4	185	196	5.6	0.074	187	208	10.1	0.001
5	238	248	4.0	0.31	258	277	6.9	0.09
6	228	255	10.6	0.006	245	274	10.6	0.02
Average	216	237	8.9		232	254	8.5	

*Probability that there is no significant difference in values

Table 4. Silage density (kg DM/m^3) at four heights (average of six samples, in depth only).

Site #	H_1	H_2	H_3	H_4	Probability*	Difference** (%)		
						H_3 - H_4	H_2 - H_4	H_1 - H_4
				Date 1				
1	306	293	302	253	<0.001	19.4	15.8	20.9
2	253	227	194	179	<0.001	8.4	26.8	41.3
3	255	229	210	203	0.004	3.4	12.8	25.6
4	216	193	190	186	<0.001	2.2	3.8	16.1
5	269	254	251	217	0.006	15.7	17.1	24.0
6	‡	275	251	240	0.03	4.6	14.6	
Average	260	245	233	213		8.9	15.1	25.6
				Date 2				
1	319	289	292	275	0.001	6.2	5.1	16.0
2	265	242	238	221	0.34	7.7	9.5	19.9
3	245	237	235	213	0.06	10.3	11.3	15.0
4	225	222	198	186	0.001	6.5	19.4	21.0
5	310	292	264	242	<0.001	9.1	20.7	28.1
6	‡	299	279	245	0.005	13.9	22.0	
Average	273	264	251	230		8.9	14.7	20.0

* Probability that there is no significant difference in values at the site

** H_1, H_2, H_3, and H_4 are, respectively, 0.5 m from the ground, intermediate 1, intermediate 2, and 0.5 m from the top

‡ The sample at H_1 for site #6 was taken in a layer of perennial grass silage laid at the bottom of the silo and covered with corn silage.

densities for individual sites could be due to possible changes in the packing pattern during silo filling (more or less time for packing specific loads because of breakdowns, intermediate work stoppages before the silo is filled, etc.). Continuous monitoring during packing would be required to better understand specific variations in density at intermediate silage heights. Overall results indicate nonetheless that average density continued to increase with increasing silage height as suggested by the logarithmic model used by Savoie et al (2004).

Density as a function of lateral position. Table 5 indicates that the density was higher in the centre than near the walls 11 times out of 12, of which 8 times were significantly higher ($p < 0.05$) . In one case however (site 4, date 1), the density was significantly higher at the wall than in the centre. Averaged over both dates and six sites, the density in the centre was 7% higher than the density near the wall. This reflects the general trend of packing tractor wheels running more frequently near the centre than near the side walls. To obtain relatively uniform density, the operator of the packing tractor might need to pay more attention to time spent near the wall compared to time spent near the centre of the silo.

Average compacted density

The previous analysis provided details on the 3-dimensional variation of density in bunker silos. This information is of

Table 5. Silage density (kg DM/m^3) at the wall and at the centre (average of 12 samples, in depth only; nine samples at site #6).

Site #	Date 1				Date 2			
	Wall	Centre	Difference (%)	Probability* (%)	Wall	Centre	Difference (%)	Probability (%)
1	282	295	4.4	0.02	286	301	5.0	0.02
2	204	223	8.5	0.04	233	249	6.4	0.33
3	207	242	14.5	0.001	225	240	6.3	0.08
4	199	194	-2.6	0.02	201	215	6.5	0.04
5	233	263	11.4	0.004	259	294	11.9	<0.001
6	251	260	3.5	0.39	257	291	11.7	0.01
Average	229	246	6.6		244	265	8.0	

*Probability that there is no significant difference in values

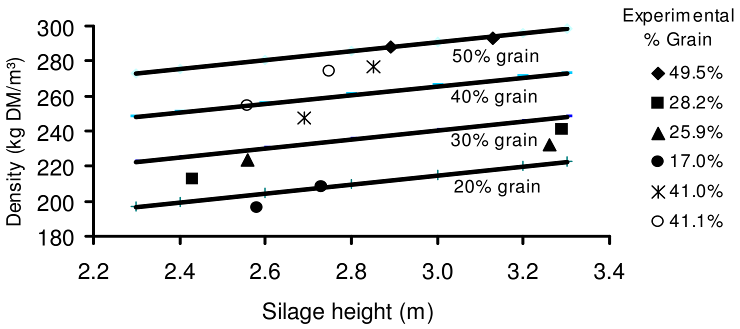

Fig. 4. Experimental dry matter density (averaged over 24 samples per silo and per date) compared to model prediction curves from Eq. 4 as a function of percentage of grain at harvest and silage height.

interest because of the high correlation between density and silage quality. The lower densities observed at the face, on top and near the sidewall indicate areas where the silage might be of lesser quality due to oxidation. The analysis also suggests practices to improve filling and unloading.

For planning a feeding program, farmers also need to know the average silage density and the total capacity of the bunker silo. The following analysis focuses on the average compacted density of an entire silo cross-section. It is based on 12 average density values from the six sites sampled at two dates. Each density value is an average of 24 samples taken in-depth (180 to 360 mm from the vertical face). These average in-depth compacted densities were 288, 213, 224, 196, 248, and 255 kg DM/m³ at the first date and 293, 241, 232, 208, 277, and 274 kg DM/m³ at the second date, for the six sites respectively (Table 3). The silage height at the second observation date was always higher than the silage height at the first observation date, for all six sites (Table 2). This is because the second sampling was further back and all bunker silos had a slightly downward slope from the back to the front end.

In a step-wise regression between average in-depth density and five independent variables, three factors (packing factor, silage moisture content, and mean particle length) were successively deleted because they were not statistically significant with probability levels of 0.768, 0.806 and 0.247, respectively. Only the percentage of grain ($p < 0.001$) and the silage height ($p = 0.020$) were significant. The prediction model, Eq. 4, had a correlation coefficient $R^2 = 0.945$.

$$\rho_{ave} = 87.7 + 2.55\%Grain + 25.5H \tag{4}$$

where:

ρ_{ave} = average in-depth silage density (kg DM/m³) and

H = silage height (m) at the measured bunker cross-section.

Partial correlation coefficients were 0.897 for percentage of grain and 0.151 for silage height.

In the present experiment, total tractor mass used for packing ranged from 5.6 t (site #4) to 12.8 t (site #1). Meanwhile, harvest rate ranged from 5.1 t DM/h (site #4) to 22.0 t DM/h (site #1). The expected high compaction effect from a heavy tractor mass was partially offset by a high harvest rate. Another reason why the packing factor did not significantly affect the density is possibly the large range of grain percentage (between 17 and 50%). The packing factor was highest at site #2 (1.32 t-h/t DM with a heavy tractor of 10 t and a low harvest rate of 6.8 t DM/h) but the associated in-depth density was the second lowest out of six sites at date 1 (213 kg DM/m³) and the third lowest at date 3 (241 kg DM/m³, Table 3). Such a low density despite a high compaction factor might be explained by the relatively low percentage of grain (28%). Indeed, three other sites (#1, 5, and 6) had a higher average in-depth density (248 to 293 kg DM/m³) and also a higher percentage of grain (41 to 50%) which apparently outweighed the compaction factor (0.53, 0.43, and 0.85 t-h/t DM, respectively) in explaining high density. Data provided by ASAE (1999) for tower silos also indicated that the average density of high moisture grain, in the order of 270 kg DM/m³, is much higher than the average density of fibrous forage, in the order of 140 kg DM/m³ for a typical 6 m diameter by 18 m high silo. A higher proportion of grain would naturally increase the density of corn silage.

The percentage of grain, which ranged between 17 and 50%, was the single most important variable to explain variation in silage dry matter density. Silage height which ranged from 2.43 to 3.29 m was also significant but to a lesser degree than percentage of grain. Figure 4 illustrates the average values of compacted densities and the model predictions based on Eq. 4 within the experimental range of significant variables. From these results, the single most efficient way to increase density would be to chose a cultivar that matures early and produces a high percentage of grain prior to silage harvest.

Validation of prediction model. A third series of density samples was taken in May 2004 at the same six sites. The average densities based on 24 in-depth samples were 291, 261, 257, 172, 266, and 274 kg DM/m³, respectively. The average silage heights were 3.35, 3.81, 3.30, 1.83, 2.44, and 2.13 m, respectively. The percentages of grain measured in the fermented silages were 37.7, 27.4, 18.4, 14.7, 33.4, and 35.2%, respectively. It should be noted that the percentages of grain measured in the fermented silages were all less than the percentages of grain measured in the original crop at harvest, prior to fermentation. The average difference was 6% units (33.8% of grain measured on average at harvest at the six sites compared to 27.8% of grain measured in the fermented silages after eight months of storage). The smaller fraction of grain measured in the fermented corn silage is probably due to physical and chemical breakdown during storage. Part of the starch is converted into organic acids and another part is simply oxidized.

When experimental values of grain percentage at harvest and silage height of this third series of measures were used in Eq. 4, the predicted densities underestimated actual densities by an average of 2.9% (range of –9.9% to +3.1% error). When the fermented grain percentages were used, the predicted densities underestimated actual densities by an average of 8.7% (range of –15.4% to –0.3% error). Equation 4 should therefore be used only with percentages of grain estimated at harvest, not after fermentation.

CONCLUSIONS

1. Dry matter density in bunker silos varied according to position of samples in a cross-section. Samples taken in-depth (180 to 360 mm from the vertical face) were always denser than samples taken at the surface (0 to 180 mm from face) by an average of 9%. Samples taken near the top of the silo were always less dense than samples taken near the floor by an average of 23%. Samples taken at the centre were generally denser (11 cases out of 12) than samples taken near the wall by an average of 7%.
2. A pattern of 24 holes cored at two depths illustrated density variation according to sampling position. The average in-depth density (180 to 360 mm from the face) of 24 samples was considered a good representation of the stored silage for a given cross-section. The average in-depth density at six sites observed at two dates ranged from 196 to 293 kg DM/m³. When these values were correlated with five variables (grain percentage, silage height, mean particle length, moisture content at harvest, and a packing factor proportional to tractor mass and inversely proportional to harvest rate), only the first two variables were retained in a regression model obtained by step-wise deletion of non-significant variables ($p = 0.05$). The model predicted density with an R^2 of 0.945 for the experimental range of 17 to 50% for grain percentage at harvest and 2.4 to 3.3 m for silage height. Partial correlation was 0.897 for grain percentage and 0.151 for silage height.
3. In the present study, the percentage of grain at harvest was the single most important factor to increase dry matter density in bunker silos. Selection of a well maturing cultivar and harvesting at the proper maturity stage are crucial to obtain high grain content and high density at storage.

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