Density profile of herbage silage in bunker silos

Philippe Savoie and Luc D'Amours

Soils and Crops Research and Development Centre, Agriculture and Agri-Food Canada, 2560 Hochelaga Blvd., Québec, Québec G1V 2J3, Canada. Email: philippe.savoie@fsaa.ulaval.ca

Savoie, P. and D'Amours, L. 2009. **Density profile of herbage silage in bunker silos**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. **50**: 3.57–3.65. Seven dairy farms were monitored during bunker silo filling with chopped grass and legume forage (herbage) in first or second cut. The average harvest rate on each farm ranged from 18 to 30 t/h with moisture content between 55 and 68%. The particle size of chopped forage averaged 15 mm and ranged from 11 to 18 mm. The smallest bunker silo was 4.9 m wide by 21.3 m long by 3.05 m high (theoretical volume of 318 m^3); the biggest silo was eight times larger by volume (15.2 m by 46.0 m by 3.7 m or 2587 m^3). Tractors weighing between 5200 and 10 000 kg were used to pack the fresh forage in the silos. The fraction of time dedicated to compaction over filling time varied between 0.20 and 1.00 h/h. A grid of 24 holes was cored in each bunker silo at two distances from the feed out face (0-180 mm and 180-360 mm). Density expressed on a dry matter (DM) basis ranged between 61 and 470 kg DM/m^3 with an average of 241 kg DM/m^3. Density at the face was on average 15% lower than density in-depth (180–360 mm from face). Samples near the floor were on average 58% denser than samples near the top. Samples at the centre were denser than samples near the wall by an average of 9%. The average in-depth density from 13 bunker cross-sections ranged from 206 to 354 kg DM/m^3; it was highly and positively correlated with a compaction index, proportional to tractor mass and packing time, and inversely proportional to harvest rate. It was negatively correlated with moisture content. Mean particle length and silage height did not have a significant effect on average in-depth density. **Keywords:** Silage, density, packing, grass, bunker, model.

Sept fermes commerciales ont fait l'objet d'un suivi lors du remplissage et du compactage de l'ensilage d'herbe de 1ère et de 2e coupes dans des silos couloir. Le taux de récolte moyen sur les fermes variait de 18 à 30 t/h avec une teneur en eau entre 55 et 68%. La longueur de hachage moyenne était de 15 mm passant de 11 à 18 mm selon les sites. Les dimensions du plus petit silo étaient de 4,9 m de large, 21,3 m de long et 3,05 m de haut avec un volume théorique de 318 m^3; le plus grand silo était huit fois plus volumineux (15,2 m par 46,0 m par 3,66 m ou 2587 m^3). La masse des tracteurs utilisés pour compacter l'ensilage variait de 5200 à 10000 kg. La fraction du temps consacrée au compactage par rapport au temps de remplissage variait entre 0,20 et 1,00 h/h. Les silos ont été échantillonnés selon une grille de 24 trous à deux distances de la face verticale par trou (0 à 180 mm et 180 à 360 mm). La masse volumique d'échantillons individuels a varié de 61 à 470 kg MS/m^3 (moyenne de 241 kg MS/m^3). Les échantillons en profondeur (180 à 360 mm de la face verticale) étaient toujours plus denses que les échantillons en surface, de 15% en moyenne. Les échantillons près du sommet étaient toujours moins denses que les échantillons près du plancher, de 58% en moyenne. Les échantillons au centre étaient plus denses que les échantillons près du mur, de 9% en moyenne. La densité moyenne en profondeur dans 13 silos a varié de 206 à 354 kg MS/m^3; elle était positivement et hautement corrélée avec l'indice de compaction, lui-même proportionnel à la masse du tracteur et au temps de compactage, et inversement proportionnel au taux de récolte. La densité en profondeur était également corrélée négativement avec la teneur en eau. La longueur de hachage et la hauteur de l'ensilage dans les silos n'avaient pas d'impact significatif sur la densité moyenne en profondeur. **Mots clés:** Ensilage, densité, compactage, graminées, silo couloir, modèle.

INTRODUCTION

Density is an important indicator of bunker silo management (Ruppel et al. 1995). An initially high density reduces the presence of air, subsequent oxidation and infiltration during storage. High density can also increase silo capacity. With high density, storage costs are therefore reduced on two counts: less loss and more silage per unit volume. However, attaining high density can require expensive equipment for compaction. Other management factors such as crop moisture and chop length, the method of spreading and compaction, the harvest capacity and the silage height might be controlled at almost no cost while having an effect on silage density. In the case of whole-plant corn silage density, D'Amours and Savoie (2005) observed that percentage of grain and silage height were more important to increase density than several other factors, including tractor weight.

Table 1 shows seven variables which were explicitly controlled and correlated with grass silage density in previous bunker silo studies. Moisture content was observed to be significant in three studies out of five. In general, a decrease in moisture content increased density on a dry matter basis. Length of cut was significant in only one study; a shorter length of cut tended to increase density. Other factors that were occasionally correlated positively with density included an increased time of compaction, an increased silage height, an increased pressure exerted on the forage, a reduced layer thickness and an increased tractor weight.

Predicting silage density in bunker silos is difficult partly because of the intrinsic variation within a silo. This spatial variation was shown by D'Amours and Savoie (2005) for corn silage bunker silos where samples in depth (180 to 360 mm from the face) were 9% denser than samples at the face, samples at 0.5 m from the top were 23% less dense than samples at 0.5 m from the bottom (for an average silage height of 2.8 m) and samples near the center were 7% denser than samples near the side wall. These authors concluded that a grid of 24 holes on bunker face and at two depths (0–180 mm and 180–360 mm from the

Table 1. Variables included in previous studies to predict grass silage density in bunker silos.

Grass silage studies	Moisture content	Length of cut	Compaction time	Silage height	Pressure on silage	Layer thickness	Tractor weight
Messer and Hawkins (1977)	x	x			x*		
Darby and Jofriet (1993)	x	x		x	x		x*
Bernier-Roy et al. (2001)	x*	x	x		x*	x*	
Muck and Holmes (2000)	x*	x	x*	x*	x	x*	x*
Muck et al. (2004a)	x*	x*	x		x*	x	
Muck et al. (2004b)			x				

x Variables included in the study.
* Significant effect on dry matter density (kg DM/m^3).

face) was necessary to obtain a good average. Moreover, samples distant from the face were more representative of the entire undisturbed bunker silo than samples at the face.

Bunker silos have been recommended for dairy farms with 100 cows or more because of relatively low storage cost and minimal loss when the silo is unloaded at feeding rates above 100 mm/d in summer and 75 mm/d in winter (Bodman and Holmes 1997). In eastern Canada, bunker silos have become more popular, even on small dairy farms. These farms are not always equipped with large tractors for intensive compaction, so other management techniques become even more important to increase density at low cost.

A research study was carried out with the purpose of monitoring and analyzing on-farm practices related to bunker silos. The long-term goal is to develop guidelines to improve the management of bunker silos in eastern Canada. A first experiment of monitoring corn silage density in bunker silos was reported by D'Amours and Savoie (2005). The present paper reports on a second on-farm experiment to measure actual density in bunker silos filled with grass and legume silages, more generally referred to as herbage silages. A major difference between corn and herbage is that the former contains grain which has a preponderant influence on the density: as grain percentage increases, so does dry matter density. Another difference is that herbage moisture content can be modified at the time of harvest by selecting the time of cutting, various windrow handling operations and the duration of field wilting. In the case of corn silage, moisture content cannot be controlled at the time of harvest, but it may be reduced by selecting faster-maturing cultivars at the time of seeding or by harvesting at a later stage of maturity.

The first objective of the present study was to obtain new data on the spatial variation of silage density for herbage. Factors that were considered included the mass of the compaction tractor, time of compaction, time of spreading, harvest rate and crop characteristics (chop length and moisture content). To obtain representative data in a variety of conditions, seven commercial dairy farms were selected. A second objective was to develop a model to represent these data and to compare predictions with those from a model developed at the University of Wisconsin and available in a worksheet file on the web (Holmes and Muck 2005).

METHODS

Site selection

Seven dairy farms were selected to represent a variety of bunker silo sizes and three climatic zones in eastern Canada. Three silos located in the Beauce region and one silo located in the Lower St. Lawrence region were in a similar climatic zone of about 2200 crop heat units (CHU) (Bootsma 1999). The silo in Lotbinière region was in a zone of about 2400 CHU and two other silos located in the Nicolet region were in a zone of about 2600 CHU. Table 2 describes the number of milking cows, milk production average and the size of the specific bunker silo monitored on each farm. Site #4 had the smallest silo, 4.9 m wide by 21.3 m long by 3.05 m high (theoretical volume of 318 m^3), while site #1 had the largest silo, 15.2 m wide by 46.0 m long by 3.66 m high (theoretical volume of 2559 m^3, i.e., eight times larger than the smallest silo).

All seven silos had a concrete backwall. Site #2 was the only location with a silo inside a building and therefore covered by a roof. This silo was filled by unloading chopped forage from a ramp rising to the top of the backwall. Other silos were filled by unloading in the front of the bunker, usually between the two side walls. In the case of silo #4, unloading occurred outside the bunker walls so one packing tractor moved the chopped forage inside the silo and a second packing tractor moved the forage further back and compacted it inside the silo. Silos

Table 2. List of commercial dairy farms and bunker silos monitored for herbage silage density.

Site #	Region	Numberof cows	Milk production (kg cow^{-1} yr^{-1})	Silo size Width (m)	Length(m)	Height (m)	Theoretical volume (m^3)
1	Beauce	200	8400	15.2	46.0	3.66	2259
2	Lower St. Lawrence	70	7100	7.6	27.4	2.44	508
3	Lotbinière	300	11000	10.1	30.5	4.67	1439
4	Nicolet	40	8000	4.9	21.3	3.05	318
5	Beauce	230	9800	9.14	46.0	3.66	1539
6	Beauce	70	9000	4.6	28.7	2.44	322
7	Nicolet	40	9300	7.9	24.1	2.44	465

#1, 2, 4 and 5 were filled with first cut herbage while silos #3, 6 and 7 were filled with second cut forage.

Variables measured at filling

Each site was visited one day during silo filling, in June 2004 for sites #1, 2, 4 and 5 and in July 2004 for sites #3, 6 and 7. The average net capacity of forage wagons was estimated by weighing several filled and empty wagons with a dynamic low-speed-weighing-in-motion scale ($\pm$25 kg, Mikros System Ltd, Pretoria, South Africa). The average harvest rate was obtained by counting the number of wagon loads arriving at the bunker over a measured time period, typically over a 3- to 4-h period. The mass of packing tractors was also measured with the dynamic scale.

The time to spread forage across the bunker (spreading time) and the time to roll over the forage without spreading (pure compaction time) were measured continuously, typically during a 1-h observation period per day of harvest. The spreading time was considered as compaction time as long as the tractor was moving forage within the walls of the bunker. The fraction of time dedicated to compaction was therefore estimated as the sum of the spreading time inside the bunker walls plus the pure compaction time divided by the total time between the arrival of two loads. This fraction is 1.0 if the packing tractor runs all the time inside the silo walls. It is generally less than 1.0 to account for idle time, external movement when the packing tractor displaces forage outside the silo walls and time devoted to other chores during the harvest period. This fraction is estimated for each compaction tractor as follows:

$$f_c = (t_s + t_c)\, n_{hwl} \quad (1)$$

where f_c is the fraction of time dedicated to compaction, t_s is the spreading time inside the bunker walls (h/load), t_c is the pure compaction time inside the bunker walls (h/load), and n_{hwl} is the number of harvested wagon loads per unit time (loads/h).

A compaction intensity index was developed based on variables that were easily measured on the commercial farms. It is different from the packing factor of Muck and Holmes (2000), which included tractor mass, layer thickness, packing time and forage dry matter, and which explained only 18% of density variation. Dry matter content is considered later, while layer thickness is difficult to estimate accurately. The new proposed index is proportional to tractor mass and the fraction of time dedicated to compaction, and inversely proportional to the rate of harvest.

$$I = m_T * f_c / Q_r \quad (2)$$

where I is the compaction intensity index [h], m_T is the tractor mass (t), and Q_r is the harvest rate of forage on a dry matter basis (t /h).

At the time of harvest, the bulk density of freshly chopped forage 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 capacities (9.5, 20.7 and 33.2 L). 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 103°C to estimate moisture content (ASAE 2002a).

On each day of harvest, three other samples of about 2.5 kg of forage were conserved to measure the actual particle length according to the standard method (ASAE 2002b).

Measured variables at feeding

After all silos had been sealed for fermentation and reopened for feeding, sites #1 to 6 were visited twice and site #7 was visited once for core sampling at the open face. The sampling dates spanned between October 14, 2004 and April 4, 2005.

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 distance from the silage face (just at the face or at a horizontal distance from the face). Three replications corresponded to three vertical lines at each lateral position. Fig. 1 illustrates the 24 positions of core sampling. Normally, 48 samples were taken with 24 samples at the face (0 to 180 mm from the surface) and 24 samples in depth (180 to 360 mm from the face). Some samples in depth could not be obtained because of very high density and extreme difficulty in cutting a proper core sample.

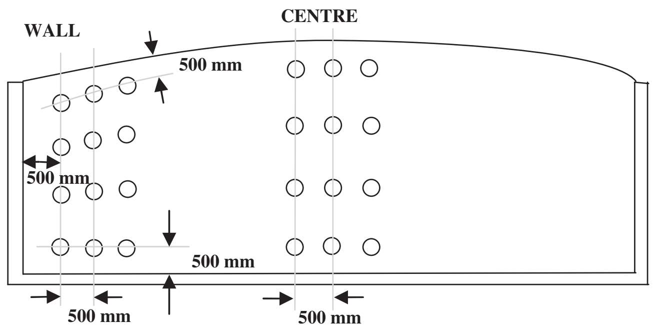

Fig. 1. Core sampling pattern to determine the silage density profile. A total of 48 samples were normally taken at each site and each date from the 24 holes illustrated at two distances from the face: 0 to 180 mm and 180 to 360 mm. Core auger inside diameter was 73 mm (not to scale).

The four heights were taken as follows: 0.5 m from the floor (H_1), 0.5 m from the top of the silage (H_4) and at two intermediate heights (H_2 and H_3). Sampling points were selected so that segments H_1-H_2, H_2-H_3, and H_3-H_4 were equal; each segment had a distance equal to the total height minus 1 m divided by three.

Core samples were taken with a gasoline-engine-powered drill fitted with an auger of 73 mm inside diameter and a length of 360 mm. A stopper on the auger was used to take an initial sample on the face (0 to 180 mm) and the full auger was used to take a second sample in the same hole up to a distance of 360 mm. Each sample had an approximate volume of 0.75 L; its wet mass was measured on site. The exact volume was based on the auger inside diameter and the actual coring distance obtained with a measuring tape after each sample was 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: the larger portion (typically 200 to 300 g wet) was used to determine the moisture content and the smaller portion (about 50 g) to determine pH and other chemical constituents not reported in the present paper. Samples were not mixed and the analysis was based on 48 individual values per silo and date. The moisture content was obtained by placing the forage in an oven for 24 h at 103°C (ASAE 2002a).

The height of the silage top was measured at six points along the ridge of the retrieved silage between the two lateral walls; these measurements allowed the calculation of an average height. Since the silage face was not perfectly vertical, an average vertical plane perpendicular to the lateral walls was estimated at half the distance between the top ridge of the retrieved silage and the tumbled silage bottom line. Between two observation dates at each site, the average distance of silage removal was estimated as the difference between the two average vertical planes. This average distance was used to estimate the feeding rate (horizontal unloading rate, mm/d).

Statistical analysis

The statistical utilities of Excel spreadsheet software were used to analyze the data for density and water content. Analysis of variance was done to identify differences between the three position factors (vertical between floor and top of silo, horizontal between on-the-face and in-depth at 180 to 360 mm from the face, and lateral near the wall or near the centre). Linear regression with step-wise deletion was used to correlate density with independent variables. A probability level of 5% was chosen to establish a significant difference.

RESULTS and DISCUSSION

Filling and packing bunker silos

The main variables recorded during filling and packing of bunker silos are presented in Table 3. The average moisture content at filling ranged from 55 to 67% between the seven sites. The average length of cut ranged from 11 to 18 mm. The harvest rate ranged from 5.7 to 10.8 t DM/h and from 18 to 30 t/h on a wet matter basis. The mass of the packing tractors ranged from 5.2 to 10 t. The spreading time and the pure compaction time both ranged from less than 2 min/load to more than 7 min/load each. The fraction of time dedicated to compaction ranged from 0.20 to 1.00. The lowest fraction was at site #4 due to the fact that the heavier tractor was outside the silo area and its spreading time was not accounted as useful time for compaction, contrary to other sites. The compaction intensity index ranged between 0.66 and 1.01 h.

Density prior to mechanical compaction

During the harvest period, a total of 63 samples were taken to estimate natural density of a thin layer of chopped herbage (0.15, 0.30 or 0.45 m thickness) prior to mechanical compaction at the seven sites. The individual values of natural density ranged from 27 to 70 kg DM/m^3, while the overall average was 43 kg DM/m^3. There was no significant difference ($p= 0.98$) between the three buckets used to estimate natural density.

There were differences in the natural densities of herbage between sites ($p< 0.001$). Average values were 41, 48, 34, 43, 47, 50 and 33 kg DM/m^3, at the seven sites, respectively. Part of the differences could be explained by differences in mean particle length (MPL, mm) and moisture content (M,% wet basis). The following model predicted the natural density of chopped herbage prior to mechanical compaction ($\rho_{natural}$, kg DM/m^3) with a multiple coefficient of determination R^2 of 0.68.

$$\rho_{\text{natural}} = 113 - 0.80 \times \text{M} - 1.35 \times \text{MPL} \qquad (3)$$

Compacted density of herbage silage

After mechanical compaction and a storage period between 3 and 9 months, 591 core samples of silage were

Table 3. Average values of variables measured during silo filling.

Site identification	1	2	3	4		5	6	7
Moisture content (%)	66.5	66.4	66.9	56.7		55.3	61.3	67.7
Mean chop length (mm)	15.9	14.2	17.8	15.6		17.5	11.4	13.4
Number of wagon loads/h	4.2	4.04	6.84	7.9		4.1	4.25	4.92
Harvest rate (t DM/h)	8.8	7.5	9.9	10.8		9.5	7.4	5.7
Wet harvest rate (t/h)	26.7	22.3	29.9	24.9		21.3	19.1	17.6
No. of compaction tractor(s)	1	1	1	2		1	1	1
Tractor mass (kg)	8550	6050	9130	6850	5760	9980	5630	5170
Spreading time (min:s/load)	05:40	07:03	05:21	03:50	01:54	07:10	07:41	02:51
Compaction time (min:s/load)	06:47	07:03	02:58	01:30	05:42	06:55	04:58	04:59
Fraction of compaction time	0.87	0.95	0.94	0.20	1.00	0.96	0.90	0.64
Compaction index*	0.85	0.77	0.88	0.66		1.01	0.85	0.68

*Compaction index is calculated by Eq. (2) and units are h.

obtained at two dates for the first six sites and at one date for the seventh site (theoretically 48 samples per site and per date, or 624 total samples). Some samples could not be obtained, specifically at sites #3 and #5 at a distance of 180 to 360 mm from the face, because the silage was too hard to obtain a complete cylindrical sample. Fig. 2 shows the distribution of density of individual samples which ranged from 61 to 470 kg DM/m^3, with an average of 241 kg DM/m^3. The moisture content of these samples ranged from 47.3 to 84.6% with an average of 66.1%.

The density distribution was analyzed as a function of the three position factors: distance from the vertical silo face, height and lateral position, i.e., centre versus near the wall. The analysis was carried out for the individual sites and dates of sampling.

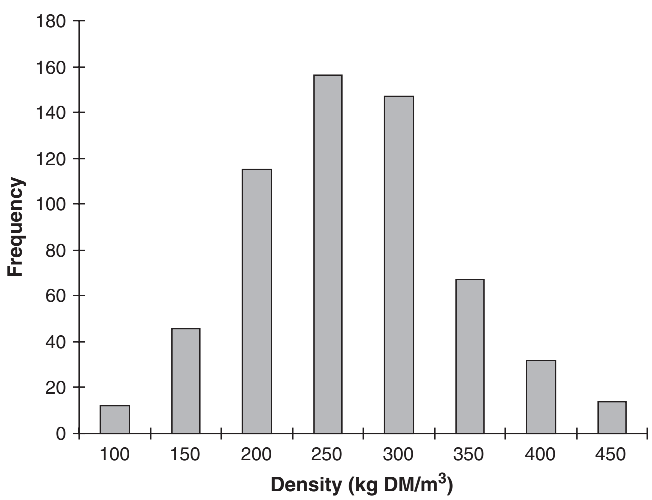

Fig. 2. Distribution of DM density of individual herbage silage samples taken at two different dates from seven bunker silos (total of 591 samples; average of 241 kg DM/m^3). The frequency is the total number of observations in the range (e.g., from 0 to 125 kg DM/m^3 for the bar above 100, 125 to 175 kg DM/m^3 for the bar above 150, etc.).

Density as a function of distance from the face Results in Table 4 show that the DM density at the vertical surface of the bunker (0 to 180 mm from the face) was always lower than the density inside the silo (180 to 360 mm from the face). The difference was statistically significant 4 times out of 9. Averaged over dates and sites, the density was reduced by 15% at the surface compared with density in-depth. The density reduction varied between sites and dates, ranging from 9 to 28%. These differences in density reduction could be the result of differences in unloading equipment and methods of removing silage from the bunker face. Information in Table 7 allows to group data at farms using the loader (sites #1, 2 and 6) or the rotary cutter (sites #3, 4, 5 and 7) for silage removal. There was practically no difference in density reduction at the face between the two groups of farms: the reduction was 38 kg DM/m^3 (15.6%) at farms using loaders and 41 kg DM/m^3 (14.7%) at farms using rotary cutters. However, farms with the rotary cutter compacted the silage on average to a much higher in-depth density (281 kg DM/m^3) than farms with the loader (248 kg DM/m^3).

Because in-depth density was always higher than 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). Since several in-depth data were missing from sites #3 and 5, these sites were not included in subsequent analyses.

Density as a function of height Table 5 indicates that density was always lowest at 0.5 m from the top, i.e., at position H_4, where it averaged 178 kg DM/m^3. Density gradually increased as silage height increased up to point H_1 located at 0.5 m from the floor where density averaged 281 kg DM/m^3. The average height of silage was 3.42 m over the seven sites and two dates (Table 7). On average, the DM density increased 30% between H_4 and H_3 (0.8 m

Table 4. **Silage density (kg DM/m^3) at the vertical surface (0 to 180 mm from the face) and in-depth (180 to 360 mm from the face) for seven sites and two dates (average of 24 samples per density value except sites #3 and 5).**

Site #	Date 1				Date 2			
	Surface	In-Depth	Diff.(%)	Prob.	Surface	In-Depth	Diff.(%)	Prob.
1	179	222	19.4	0.643	217	252	13.3	0.050
2	179	250	28.4	<0.001	178	206	13.6	0.197
3	245	278	11.9	NA*	243	304	20.1	NA*
4	187	243	23.0	<0.001	197	230	14.3	0.050
5	302	351	14.0	NA*	304	340	10.6	NA*
6	263	288	8.7	0.068	242	270	10.4	0.057
7	199	218	8.7	0.318	–	–	–	–
Avg.	222	264	16.3	–	230	267	13.8	–

*Statistical analyses were not available because several samples could not be cored in-depth due to excessive hardness of samples (number of missing data: 12 and 8 at site #3 and 9 and 4 at site #5, for dates 1 and 2, respectively).

lower), 48% between H_4 and H_2 (1.6 m lower) and 58% between H_4 and H_1 (2.4 m lower). The analysis of variance comparing density at the four heights indicated statistical differences 8 times out of 9.

In all cases, density near the top of the silo at H_4 was the lowest. In 8 cases out of 9, density near the bottom floor at H_1 was the highest. Exceptionally at site #2 for date 1, intermediate density at H_2 was higher than density at H_1. Site #2 was filled differently from all others, with wagons being unloaded from a ramp behind the backwall. The packing tractor could not enter the silo before enough loose forage was piled above the height of the backwall, which could explain a lower compaction at the bottom. Overall, results indicate that 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 6 indicates that the density was higher in the centre than near the walls 7 times out of 9, 4 of them significantly ($p < 0.05$). In one case, however (site 2, date 1), the density was higher near the wall than in the centre. Averaged over both dates, density in the centre was 9% higher than density near the wall. This reflects a general trend of packing tractor wheels running more frequently near the centre than near the side walls.

Average compacted density

The compacted density measured in-depth (180 to 360 mm from the vertical face) was averaged for each site and each date of sampling. Each value represented the average density of a silo cross-section. These values ranged from 206 to 354 kg DM/m^3 (Table 7). The 13 average values of

Table 5. **In-depth silage density (kg DM/m^3) and probability of significant difference between 4 heights according to site and date of sampling between Oct. 14, 2004 and Apr. 4, 2005.**

Site #	Date	Density at 4 heights§				Prob.	Difference (%)		
		H_1	H_2	H_3	H_4		H_3-H_4	H_2-H_4	H_1-H_4
1	10/14	282	245	200	160	<0.001	25.0	53.1	76.3
2	10/21	269	306	271	154	<0.001	76.0	98.7	74.7
3	10/28	*	*	*	*	*	*	*	*
4	11/07	280	260	227	206	<0.001	10.2	26.2	35.9
5	01/17	*	*	*	*	*	*	*	*
6	01/24	324	302	279	246	0.004	13.4	22.8	31.7
7	04/04	250	231	224	168	0.059	33.3	37.5	48.8
1	01/31	299	290	243	178	<0.001	36.5	62.9	68.0
2	02/14	285	236	188	114	<0.001	64.9	107	150
3	02/24	*	*	*	*	*	*	*	*
4	02/07	233	222	188	144	<0.001	30.6	54.2	61.8
5	03/14	*	*	*	*	*	*	*	*
6	03/07	308	274	257	236	0.013	8.9	16.1	30.5
Avg.		281	263	231	178	–	29.8	47.8	57.9

§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.
*Insufficient density data in-depth for height comparisons at sites #3 and 5.

Table 6. Silage density (kg DM/m^3) at the wall and at the centre (in depth).

	Date 1				Date 2			
Site #	Wall	Centre	Diff.(%)	Prob.	Wall	Centre	Diff.(%)	Prob.
1	211	233	9.4	0.032	247	257	3.9	0.446
2	257	244	−5.3	0.351	200	212	5.7	0.292
4	243	243	0.0	0.959	209	251	16.7	0.030
6	282	294	4.1	0.347	248	289	14.2	0.010
7	172	264	34.8	<0.001	–	–	–	–
Avg.	233	256	8.6	–	226	252	10.1	–

density were analyzed by regression with step-wise deletion of non-significant factors among four variables: moisture of silage (ranging from 57.9 to 74.1%), height of silage (from 2.30 to 4.32 m), mean particle length at harvest (from 11.4 to 17.8 mm) and the compaction intensity index (from 0.66 to 1.01 h). The moisture of silage varied mainly between silos and minimally within the six silos sampled at two different dates (average of 1.5% higher moisture content at the second date of sampling within the same silo on average 12 wk later). After regression, two factors were deleted: height ($p = 0.717$) and mean particle length ($p = 0.142$). The two other factors, moisture and compaction index, were highly significant: $p = 0.015$ for moisture and $p < 0.001$ for compaction index. The following equation to predict average compacted density (ρ_{ave}, kg DM/m^3) had an $R^2 = 0.916$.

$$\rho_{ave} = 223 - 3.02 \times M + 294 \times I \quad (4)$$

The total silage height did not significantly affect density of herbage silage in the present experiment. However, silage height significantly influenced density in a previous report on corn silage by D'Amours and Savoie (2005). This difference between herbage and corn may be due to greater variability observed in herbage bunker silos, due to variation in moisture content during field wilting and at harvest. Also, there can be an opposite effect between silage height and density. For example when a fixed mass of chopped forage is spread over the entire bunker floor, the density becomes higher as the height becomes smaller. If the same mass is less compacted, silage height will be higher and compacted density will be less. To ensure maximum density of herbage in a bunker, an equilibrium between spreading horizontally and piling vertically is likely to be necessary.

The prediction model (Eq. 4) was compared with the model of Holmes and Muck (2005) over the experimental range of compaction index. In Eq. 4, the fraction of time dedicated to compaction was assumed to be 0.9 (f_c in Eq. 2). The range of the compaction index for simulation, between 0.7 and 1.0, is equivalent to a range of a packing tractor mass between 6.2 and 8.9 t for a harvesting rate of 8 t DM/h (a value near the experimental average of 8.5 t DM/h). Fig. 3 shows that the initial densities for both models were similar at a low compaction index of 0.7 h (e.g., densities were about 220 kg DM/m^3 at 70% moisture

Table 7. Average values of variables measured at first and second dates during feeding.

	Site number						
Variable	1	2	3	4	5	6	7
Density (in depth, 1st date)*	222	250	279	243	354	288	218
Density (in depth, 2nd date)*	252	206	304	229	340	268	–
Moisture content (1st date,%)	74.1	68.0	66.3	60.4	62.4	57.9	76.7
Moisture content (2nd date,%)	71.3	71.7	67.6	63.9	61.6	60.0	–
Silage height(1st date, m)	3.78	3.73	3.44	2.55	4.24	2.79	2.30
Silage height (2nd date, m)	3.81	3.33	4.32	3.12	4.13	2.98	–
Unloading equipment	Loader	Loader	Rotary cutter	Rotary cutter	Rotary cutter	Loader	Rotary cutter
Feeding rate between dates (mm/d)	170	134	107	96	157	182	–

*Density units, kg DM/m^3.

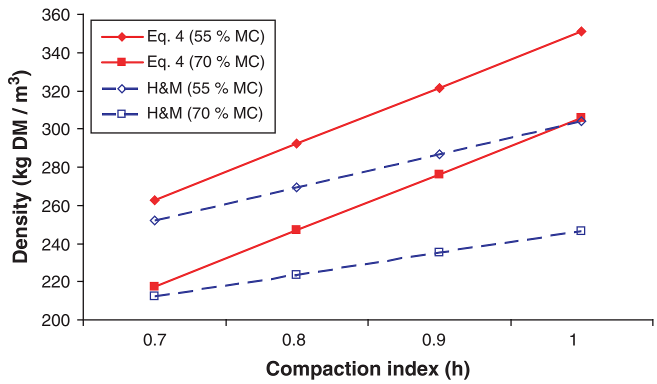

Fig. 3. Predicted average DM density of herbage in a bunker silo as a function of a compaction index (the range 0.7 to 1.0 h is equivalent to a packing tractor mass between 6.2 and 8.9 t for a harvest rate of 8 t DM/h) using the Holmes and Muck (2005) model (H & M) and Eq. 4 at 55 and 70% moisture content (MC).

content and 260 kg DM/m^3 at 55% moisture). However, the model of Holmes and Muck (2005) predicted a smaller increase in density as the compaction index increased with a difference close to 60 kg DM/m^3 at a moisture content of 70% and an index of 1.0 h. Equation 4 reflects the particular set of experimental data where a combination of heavy tractor, high fraction of time dedicated to compaction and low harvest rate resulted in relatively high DM density.

Equation 4 should not be extrapolated for compaction index values outside the experimental range (0.66 to 1.01). For example, a 10 t packing tractor and a slow harvest rate of 6 t DM/h are two variables that could be met individually within the experimental range (Table 7), but not in combination, with a resulting compaction index of 1.5 h (assuming a fraction of dedicated time to compaction of 0.9). The extrapolated average density based on Eq. 4 would be 498 kg DM/m^3 and unrealistically high, since not a single individual sample out of 591 attained such a level. The relationships in Eq. 4 will therefore not remain linear for values of M and I outside the experimental range.

In the current study, the two most important variables to influence herbage silage density were compaction index and moisture content. The compaction index and the density could be increased by increasing the packing tractor mass, by using the compaction tractor as much as possible without idling, by increasing the number of tractors and by decreasing the harvest rate. The density could also be increased by reducing the moisture content. In practice, the main choice would be to increase the mass of the packing tractor as the harvest rate increases.

CONCLUSION

1. DM density of herbage 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 15%. Samples taken near the bottom of the silo were always denser than samples taken near the top by an average of 58%. Samples taken at the centre were generally denser (7 cases out of 9) than samples taken near the wall by an average of 9%.
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 and a seventh site at one date was well correlated with moisture content and a compaction index ($R^2 = 0.916$), and not significantly affected by length of cut and silage height.
3. A linear regression model predicted the average in-depth density, which ranged experimentally from 206 to 354 kg DM/m^3, while moisture content of silage ranged from 58 to 74% and the compaction index from 0.66 to 1.01 h. This range of compaction index was equivalent to a tractor mass between 6.2 and 8.9 t at a harvest rate of 8 t DM/h.
4. Compared with the model of Muck and Holmes (2005) for bunker silage density, the present model estimated a similar dry matter density at a low compaction index (0.70 h), but estimated a higher increase in density as the compaction index increased up to 1.0 h.

ACKNOWLEDGEMENTS

The authors thank several collaborators who identified commercial farms and provided weighing equipment for wagons and tractors: Jeannot Rodrigue, MAPAQ Lac Etchemin, Sylviane Jinchereau, MAPAQ Sainte-Marie de Beauce, Denis Ruel, Alain Fournier and Michel Beaumier, MAPAQ Nicolet. Mr. Mario Laterrière, Agriculture and Agri-Food Canada Sainte-Foy, contributed to the laboratory analyses and Jean-François Poirier, student, participated in data collection. The seven collaborating farmers are also acknowledged.

REFERENCES

ASAE. 2002a. ASAE Standard S358.2. Moisture measurement – forages. In *ASAE Standards*, 565. St. Joseph, MI: ASABE.

ASAE. 2002b. ANSI/ASAE Standard S424.1. Method of determining and expressing particle size of chopped forage material by screening. In *ASAE Standards*, 602–604. St. Joseph, MI: ASABE.

Bernier-Roy, M., Y. Tremblay, P. Pomerleau and P. Savoie. 2001. Compaction and density of forage in bunker silos. ASAE Paper No. 011089. St. Joseph, MI: ASABE.

Bodman, G.R. and B.J. Holmes. 1997. Managing and designing bunker and trench silos. Agricultural Engineers Digest AED 43, Ames, IA: MidWest Plan Service.

Bootsma, A. 1999. Average crop heat units available for corn and soybean in E. Canada. http://sis.agr.gc.ca/cansis/nsdb/climate/crop_heat/intro.html (2009/01/30).

D'Amours, L. and P. Savoie. 2005. Density profile of corn silage in bunker silos. *Canadian Biosystems Engineering / Le génie des biosystèmes au Canada* 47: 2.21–2.28.

Darby, D.E. and J.C. Jofriet. 1993. Density of silage in horizontal silos. *Canadian Agricultural Engineering* 35: 275–280.

Holmes, B.J. and R.E. Muck. 2005. Bunker silo density calculator and documentation. http://www.uwex.edu/ces/crops/uwforage/storage.htm (2009/01/30).

Messer, H.J.M. and J.C. Hawkins. 1977. The influence of the properties of grass silage on bulk density and horizontal pressure. *Journal of Agricultural Engineering Research* 22: 55–64.

Muck, R.E. and B.J. Holmes. 2000. Factors affecting bunker silo densities. *Applied Engineering in Agriculture* 16: 613–619.

Muck, R.E., P. Savoie and B.J. Holmes. 2004a. Laboratory assessment of bunker silo density, part I: Alfalfa and grass. *Applied Engineering in Agriculture* 20: 157–164.

Muck, R.E., B.J. Holmes and P. Savoie. 2004b. Packing practice effects on density in bunker silos. ASAE Paper No. 041137. St. Joseph, MI: ASABE.

Ruppel, K.A., R.E. Pitt, L.E. Chase and D.M. Galton. 1995. Bunker silo management and its relationship to forage preservation on dairy farms. *Journal of Dairy Science* 78: 141–153.

Savoie, P., R.E. Muck and B.J. Holmes. 2004. Laboratory assessment of bunker silo density, part II: Whole-plant corn. *Applied Engineering in Agriculture* 20: 165–171.