FACTORS AFFECTING BUNKER SILO DENSITIES

R. E. Muck, B. J. Holmes

ABSTRACT. *High densities in bunker silos minimize losses and reduce storage costs; however, the guidelines to attain high densities are based on relatively little research. The objective of this study was to determine those practices or factors most correlated with bunker silo density. Density was measured in 175 bunker silos across Wisconsin using core samples collected at chest height (1.13 m, 3.70 ft, on average) across the feed-out face. Silo filling practices were surveyed and correlated with density. Most silages sampled were alfalfa or corn. Dry matter densities ranged from 106 to 434 kg/m^3 (6.6 to 27.1 lb/ft^3). The core densities were correlated with the height of silage above the core, indicating the effect of self-compaction. To adjust for this, all densities were corrected for the median depth below the surface (2.16 m or 7.09 ft) using the equations of Pitt (1983) for density with height for the center of tower silos. The adjusted dry matter densities were most strongly correlated with how thinly a load was spread (L), tractor weight (W), packing time per tonne as-fed (T), and dry matter content (D). These four factors were combined into a packing factor [W (TD)$^{1/2}$ L^{-1}] that explained 18.2% of the variation in dry matter density. Additional factors such as the use of dual wheels, etc. did not significantly improve the prediction of dry matter density. An equation was developed to predict average density in a bunker silo based on the packing factor plus crop height in the silo.*

Keywords. *Silage, Silos, Density, Packing, Tractor, Tires, Bunker.*

Density in bunker silos on commercial farms is known to be highly variable (Ruppel et al., 1995). This significantly affects crop preservation. A high density is desirable for two reasons. First, a high density reduces the porosity of the crop, which directly affects the rate at which oxygen moves into the silage mass during filling, storage, and feed-out, and thus controls the rates of plant and microbial respiration and spoilage. Second, a higher density increases a silo's capacity. Thus, higher densities generally reduce the annual cost of storage per unit of crop by both increasing the amount of crop entering the silo and reducing crop losses.

How to produce a high density in a bunker silo is less certain. Typical guidelines are to spread the crop in layers of 15 cm (6 in.) or less using a progressive wedge technique and pack continuously during the filling process with single-wheeled tractors. However, research to confirm such guidelines is difficult to find.

Article was submitted for publication in October 1999; reviewed and approved for publication by the Power & Machinery Division of ASAE in July 2000. Presented as ASAE Paper No. 99-1016.

Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA or University of Wisconsin and does not imply approval of a product to the exclusion of others that may be suitable.

The authors are **Richard E. Muck**, ***ASAE Member Engineer***, Agricultural Engineer, USDA, Agricultural Research Service, U.S. Dairy Forage Research Center, Madison, Wisconsin, and **Brian J. Holmes**, ***ASAE Member Engineer***, Professor, Biological Systems Engineering Department, University of Wisconsin-Madison, Madison, Wisconsin. **Corresponding author:** Richard E. Muck, USDA, Agricultural Research Service, U.S. Dairy Forage Research Center, 1925 Linden Drive West, Madison, WI 53706-1108, phone: 608.264.5245, fax: 608.264.5147, e-mail: <remuck@facstaff.wisc.edu>.

In reviewing this area, Honig (1991) found most European guidelines were more or less empirical and related to tractor weight/t dry matter (DM)/h or number of compressions/t DM or packing time/t DM. He also reported model bunker silo results from Laue (1990) who observed a DM density of 90 kg/m^3 (5.6 lbs/ft^3) with a light packing tractor (2500 kg or 5500 lbs) and 160 kg/m^3 (10.0 lbs/ft^3) with a heavy packing tractor (4500 kg or 9900 lbs). Using dual wheels reduced density relative to a single wheel whereas speed of compaction (2 or 4 km/h; 1.2 or 2.4 mph) did not appear to affect density. Ruppel et al. (1995) monitored the filling of 30 bunker silos with alfalfa and/or grass on commercial farms. Silo density was correlated with various factors. The most important were packing time (min per unit top surface area) and tractor weight. Packing time per unit wet weight was not as strongly correlated to density as time per unit area.

In these studies, several potentially important factors such as tire pressure and layer thickness were not considered. Also in Ruppel et al. (1995), packing time and tractor weight together explained only a small fraction of the variation in the densities measured. As a consequence we decided to measure densities in a wide range of bunker silos, survey filling practices, and correlate the practices with the measured densities.

MATERIALS AND METHODS

Nineteen collaborating county extension agents in Wisconsin were enlisted to measure densities of selected bunker silos in their respective counties. This was done between autumn 1997 and summer 1998. The silos primarily contained either corn or alfalfa silage. Density was measured with 5-cm (2-in.) diameter corers (fig. 1). Agents were instructed to take cores at approximately chest

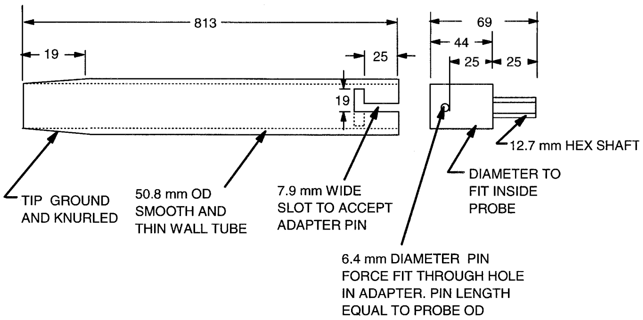

Figure 1–Schematic of corer used for measuring silage density. Dimensions in mm; multiply by 0.0394 to convert to inches. Drawing is not to scale.

height at four locations across the silage feed-out face. Average core height was 1.13 ± 0.20 m (3.70 ± 0.66 ft). Prior to coring, loose silage was brushed away from the selected locations. Using an electric drill, approximately 30-cm (12-in.) deep cores were taken. Each core was carefully transferred to an individual plastic bag, and the bag was sealed. Core depth, distance from the top of the silo, and distance from the floor were recorded. Core samples and a grab sample of silage were express mailed to the U.S. Dairy Forage Research Center for determination of core weight, moisture content, and particle size distribution. Moisture content of each sample was determined in duplicate by oven drying at 60°C for 72 h (ASAE Standard S358.2, ASAE, 1998). Particle size distribution was measured as per ANSI/ASAE Standard S424.1 SEP92 (ASAE, 1998) on the grab sample (one replicate). Densities were calculated based on the inside diameter of the corer throat and core depth.

A survey questionnaire was completed for each silo sampled. Information requested from farmers included: number of packing tractors, tractor weight, number of tires per tractor, tire pressure, tire condition, number of drive wheels, silage delivery rate, packing time per day, harvest time per day, filling time, filling technique (progressive wedge, etc.), packing speed, initial layer thickness, silo dimensions, maximum silage height, crop, crop maturity, and theoretical length of cut. These factors, DM content, and average particle size plus factors derived from them such as average wheel load, packing time/t as-fed and packing time/t DM were correlated with measured dry matter densities using linear regression techniques.

Results

Over the course of a year, 175 bunker silos were surveyed. All but seven were whole-plant corn or alfalfa silages. The seven were of diverse types and are not reported here. Several of the alfalfa silages did contain mixtures of grass or another legume but were analyzed as being alfalfa silage. The range of and mean DM contents, densities, and particle sizes for alfalfa and corn silages are shown in table 1. Average dry matter densities and particle sizes were similar for both alfalfa and corn silages although alfalfa silages had wider ranges of values. Alfalfa silage on average was drier than corn silage, and that was the principal reason for the average wet density of corn silage being 100 kg/m^3 (6 lbs/ft^3) higher than that of alfalfa

Table 1. Summary of core samples collected from 168 bunker silos

	Alfalfa Silage (87 silos)			Corn Silage (81 silos)		
Characteristic	Average	Range	Std. Dev.	Average	Range	Std. Dev.
Dry matter (%)	42	24-67	9.50	34	25-46	4.80
Wet density (kg/m^3)	590	210-980	175	690	370-960	133
Wet density (lb/ft^3)	37	13-61	10.9	43	23-60	8.3
Dry density (kg/m^3)	237	106-434	61	232	125-378	46
Dry density (lb/ft^3)	14.8	6.6-27.1	3.8	14.5	7.8-23.6	2.9
Avg. particle size (mm)	11.7	6.9-31.2	3.8	10.9	7.1-17.3	2.0
Avg. particle size (in.)	0.46	0.27-1.23	0.15	0.43	0.28-0.68	0.08

silage. Some of the highest densities in both crops were similar to values expected in tower silos (ASAE Standard D252.1, ASAE, 1998).

Dry matter densities were positively correlated ($r^2 = 0.197$; $P < 0.0001$) with the height of silage above the core (fig. 2), indicating the effect of self-compaction in bunkers. To put densities on a common basis, all densities were adjusted to the median depth below the surface (2.16 m or 7.09 ft). It was assumed the relationships developed by Pitt (1983) for predicting density with depth at the center of a tower silo (i.e., no effect of wall friction) would hold in a bunker silo. These relationships primarily assumed the ensiled forage obeyed Hooke's law except under saturated conditions. The adjustment for depth used equation 15 of Pitt (1983):

$$\gamma(z) = \gamma_o e^{K\gamma_o gz} \qquad (1)$$

where

$\gamma(z)$ = wet density at depth z
γ_o = wet density at the top of the silo (kg/m^3)
z = depth below the top (m)
K = compressibility (Pa^{-1})
g = gravitational acceleration, 9.8 m/s^2

We assumed a compressibility, K, of 1.5×10^{-5} Pa^{-1} (0.103 in.^{2}/lb), a value in the middle of the range of literature values summarized by Pitt (1983). The "Solve For" function within a Quattro Pro® spreadsheet was used to estimate the wet density at the top of the silo for each case based on the assumed compressibility. Then the density at 2.16 m (7.09 ft) was calculated within the spreadsheet. The resulting adjusted DM densities were not

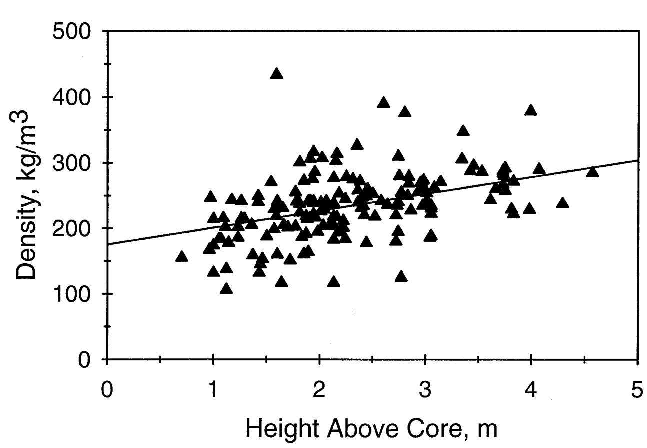

Figure 2–Dry matter densities of all silages as determined by core sampling in relation to the height of silage above the cores. (Multiply kg/m^3 by 0.0624 for lbs/ft^3, m by 3.28 for ft.)

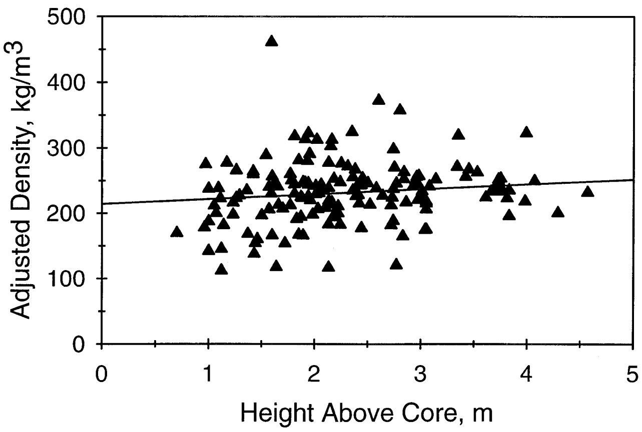

Figure 3–Dry matter densities adjusted for a common depth below the top of the silage (2.16 m or 7.09 ft) as correlated with the height of silage above the core samples. (Multiply kg/m^3 by 0.0624 for lbs/ft^3, m by 3.28 for ft.)

correlated ($r^2 = 0.020$; $P > 0.05$) with height of silage above the core (fig. 3), indicating the adjustment had removed the effect of height above the core.

The adjusted DM densities were both plotted and correlated with various factors collected in the surveys, DM content, particle size and various derived factors. Table 2 lists the correlation coefficients sorted from the highest to lowest correlation. The highest correlation was with the initial layer thickness of the forage before packing. Density decreased with increasing layer thickness. The next most important factors involved packing tractor weight (average packing tractor weight, average wheel load, total weight of packing tractors). Of these, average packing tractor weight had the highest correlation with DM density. Dry matter density increased with DM content. Bald tires appeared to improve density. Longer particles were correlated with higher density, contrary to expectations. Packing time per tonne as-fed was more strongly correlated with density than packing time per tonne DM. Other factors were poorly correlated with density although the direction of correlation was usually in the expected direction.

Table 2. Correlation of factors with adjusted dry matter density

Factor	Correlation Coefficient
Initial layer thickness	–0.279*
Average packing tractor weight	0.262*
Average wheel load	0.224*
Dry matter content	0.209*
Total weight of packing tractor(s)	0.200*
Tire condition (1 = New, 3 = Bald)	0.195*
Average particle size	0.194*
Packing time (min/t as-fed)	0.162*
Speed of packing (1 ≥ 8 km/h; 4 ≤ 1.6 km/h)	0.147
Number of packing tractors	0.146
Wheels per packing tractor	0.126
Slip during packing (1 = none; 3 = frequently)	0.101
Tire pressure	0.098
Crop (1 = corn; 2 = alfalfa)	0.086
Packing time (min/t DM)	0.078
Front wheel drive (1 = front wheel drive, assist; 2 = rear wheel drive only)	0.075
Packing method (1 = horizontal, 2 = progressive wedge, 3 = distribute only)	–0.068
Delivery wagon or truck drives over pile (1 = yes)	0.059

* Significant correlations ($P < 0.05$).

We analyzed the packing factors for cross-correlations, and the principal factors are compared in table 3. The initial layer thickness had the greatest number of significant correlations with other factors, suggesting that operators who were concerned about spreading the crop in thin layers were also doing other things to assure a high density (heavy packing tractors, more than one packing tractor, more packing time per unit crop, etc.). Particle size was correlated negatively with initial layer thickness and positively with number of packing tractors, possibly explaining the positive correlation with density. In contrast to corn, alfalfa was ensiled drier and packed longer per unit weight. This latter correlation is associated likely with the slower harvest rates in alfalfa versus corn.

We also correlated DM density with the factors of Ruppel et al. (1995), tractor weight multiplied by packing time per unit surface area and tractor weight multiplied by packing time per as-fed tonne. The factor on an area basis had a correlation coefficient of 0.080. The factor based on time per tonne as-fed had a correlation coefficient of 0.219,

Table 3. Cross-correlations (Pearson Correlation Coefficients) among packing factors

	LT†	AT	DM	TC	PS	PT	SP	NT	WT	SL	TP	CR	FD	PM
LT	1.00	–0.22*	–0.03	–0.25*	–0.18*	–0.19*	–0.45*	–0.34*	–0.26*	–0.32*	–0.25*	–0.04	–0.40*	0.26*
AT	–0.22*	1.00	–0.01	0.13	0.08	–0.16*	0.33*	0.07	0.66*	0.05	0.03	–0.05	–0.11	–0.17*
DM	–0.03	–0.01	1.00	–0.02	–0.14	0.30*	–0.02	–0.05	–0.04	–0.02	–0.10	0.44*	0.05	–0.03
TC	–0.25*	0.13	–0.02	1.00	0.12	0.12	0.18*	0.06	0.09	0.25*	0.28*	0.00	0.16*	–0.14
PS	–0.18*	0.08	–0.14	0.12	1.00	0.05	0.01	0.19*	0.08	–0.04	0.09	0.12	–0.02	0.07
PT	–0.19*	–0.16*	0.30*	0.12	0.05	1.00	0.06	–0.09	–0.14	–0.04	0.15	0.41*	0.23*	–0.07
SP	–0.45*	0.33*	–0.02	0.18*	0.01	0.06	1.00	0.15	0.17*	0.22*	0.32*	0.05	0.16*	–0.09
NT	–0.34*	0.07	–0.05	0.06	0.19*	–0.09	0.15	1.00	–0.07	0.22*	0.02	–0.10	0.11	–0.07
WT	–0.26*	0.66*	–0.04	0.09	0.08	–0.14	0.17*	–0.07	1.00	0.13	–0.16*	–0.06	0.03	–0.22*
SL	–0.32*	0.05	–0.02	0.25*	–0.04	–0.04	0.22*	0.22*	0.13	1.00	0.07	–0.09	0.24*	–0.09
TP	–0.25*	0.03	–0.10	0.28*	0.09	0.15	0.32*	0.02	–0.16*	0.07	1.00	–0.05	0.04	–0.01
CR	–0.04	–0.05	0.44*	0.00	0.12	0.41*	0.05	–0.10	–0.06	–0.09	–0.05	1.00	0.03	–0.01
FD	–0.40*	–0.11	0.05	0.16*	–0.02	0.23*	0.16*	0.11	0.03	0.24*	0.04	0.03	1.00	–0.28*
PM	0.26*	–0.17*	–0.03	–0.14	0.07	–0.07	–0.09	–0.07	–0.22*	–0.09	–0.01	–0.01	–0.28*	1.00

* Significant correlations ($P < 0.05$).

† LT, Layer thickness; AT, Average packing tractor weight; DM, Dry matter content; TC, Tire condition (1 = new; 3 = bald); PS, Particle size; PT, Packing time (min/t as-fed); SP, Speed of packing (1 ≥ 8 km/h; 4 ≤ 1.6 km/h); NT, Number of packing tractors; WT, Wheels per packing tractor; SL, Slip during packing (1 = none; 3 = frequently); TP, Tire pressure; CR, Crop (1 = corn; 2 = alfalfa); FD, Front wheel drive (1 = front wheel drive, assist; 2 = rear wheel drive only); PM, Packing method (1 = horizontal; 2 = progressive wedge; 3 = distribute only).

an improvement over the correlation with total tractor weight alone.

Like Ruppel et al. (1995), we decided to develop a packing factor that best explained the variation in DM density. One concern in developing such a factor was the range of values reported in our study for initial layer thickness. As shown in figure 4, there were a considerable number of points where the initial layer thickness was reported to be less than 10 cm (4 in.) and which did not appear to fit the trend of the other points. We felt 10 cm (4 in.) was a practical minimum spreading depth, and we analyzed only data having a layer thickness of 10 cm or greater. Using these data, the following packing factor, P, was found to account for 18.2% of the variation in dry matter density:

$$P = \frac{W}{L}\sqrt{T \times D} \qquad (2)$$

where

W = average packing tractor weight, kg (lbs)
L = initial layer thickness, cm (in.)
T = packing time, tractor h/t as-fed (h/T as-fed)
D = dry matter content, g/kg (lbs/lbs)

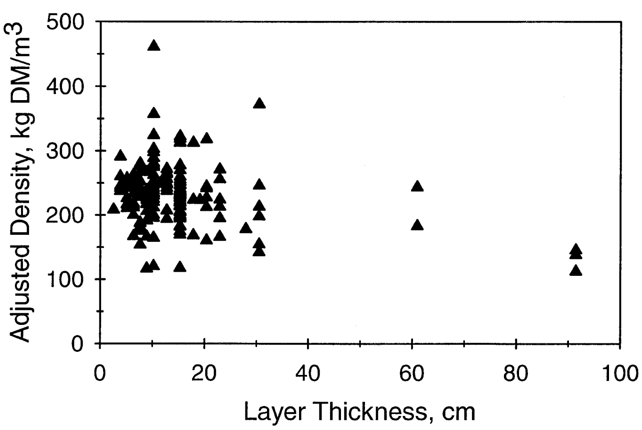

Figure 4–Adjusted dry matter densities as correlated with the initial layer thicknesses of the spread loads. (Multiply kg/m^3 by 0.0624 for lbs/ft^3, cm by 0.394 for in.)

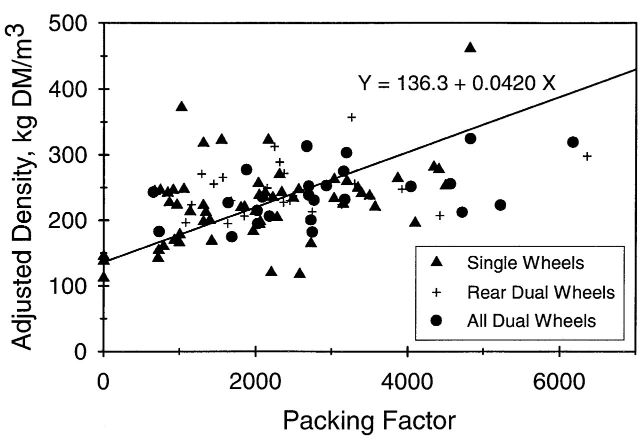

Figure 5–Adjusted dry matter density as correlated with the packing factor [W(TD)$^{1/2}$ L^{-1}] and use of dual wheels on the packing tractor. (Multiply kg/m^3 by 0.0624 for lbs/ft^3.)

No other factors improved the coefficient of determination significantly. Dry matter density as correlated with the packing factor is presented in figure 5. As an example, the data in figure 5 are segregated by wheel configuration, and there is no apparent effect on DM density of single wheels versus dual wheels.

Discussion

Factors Affecting the Consolidation of Forages

The results of the current study are reasonably consistent with previous work on the consolidation of forage crops. Packing tractor weight was one of the most important factors in the current study and has been identified in earlier studies as a key factor related to silage density (Jofriet and Zhao, 1990; Laue, 1990; Darby and Jofriet, 1993; Ruppel et al., 1995). Packing time per unit mass of crop has also been seen as important (Honig, 1991; Ruppel et al., 1995). However, in our study it appears there are diminishing returns for prolonged packing per unit mass of wet forage (fig. 6).

Other factors such as DM content and particle size have been less consistent across studies. Ruppel et al. (1995) found no correlation between DM content and silage density. However, the percentage of legume in the hay crop silages varied from 0 to 90% and was correlated with DM content, possibly influencing their results. Pitt and Gebremedhin (1989) measured the stiffness of alfalfa and grass at different moisture contents. Alfalfa had less stiffness at 35% DM than at 58% or 18% DM, suggesting a quadratic relationship. In contrast the stiffness of grass decreased with increasing DM content. Evidently, dry, brittle grass stems afforded less resistance to applied pressure than wet grass. These results suggest possibly similar relationships between density and DM content for alfalfa and grasses at normal bunker silage DM contents to that found in our study. McGechan (1990) surveyed earlier grass silage studies and found DM density of grass silage in bunker silos increased linearly as a function of DM content:

$$\rho = 46 + 0.496\ d \qquad (3)$$

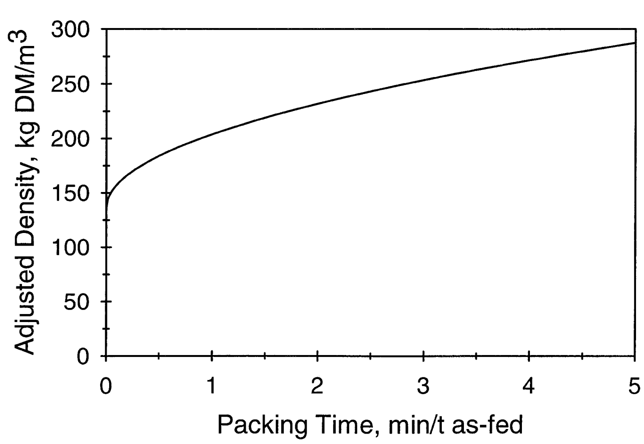

Figure 6–Calculated adjusted dry matter density as affected by packing time using the equation in figure 5 and equation 2 for a tractor weight of 10 000 kg (22,000 lbs), initial layer thickness of 15 cm (6 in.) and 35% DM. (Multiply kg/m^3 by 0.0624 for lbs/ft^3; min/t by 1.10 for min/T.)

where

ρ = bulk dry matter density, kg/m^3 (multiply by 0.0624 for lbs/ft^3)

d = dry matter content (g/kg)

However, these silages were wetter (16 to 30% DM) than the majority of silages in our study (24 to 67% DM), so a linear relationship may not hold for our drier conditions. Overall, these results suggest some positive correlation between DM density and DM content exists within the recommended ranges of DM content for bunker silos.

Effects of particle size on bunker silage densities are more ambiguous. In our study, particle size was weakly, positively correlated with DM density, the opposite of what one would expect. Possibly there was some correlation with maturity, but maturity estimates in the survey appeared unreliable. However, particle size was significantly correlated with initial layer thickness and number of packing tractors (table 3), which could possibly explain the unexpected results. Ruppel et al. (1995) found no correlation between particle size and density. In alfalfa, Shinners et al. (1994) observed the initial bulk density in a bunker silo was reduced 14% as geometric mean particle size was increased from 8.7 to 25.2 mm (0.34 to 0.99 in.). Final wet and dry bulk densities were reduced 12% and 21%, respectively. Pitt and Gebremedhin (1989) performed compression tests on alfalfa and grass at two chop lengths (6.4 and 12.7 mm; 0.25 and 0.50 in.). In alfalfa, the stiffness was not significantly affected by chop length. In grass, there was an increase in stiffness with longer chop length at the lower DM contents (20% and 27%). These results were quite variable and may have been confounded by variations in the fiber content of the forage, which is also known to affect material stiffness (McGechan, 1990). Finally, the review of McGechan (1990) found literature sources which suggested that ensiled density of grass silages in bunker silos would decrease by approximately 20% as median chop length increases from 20 to 100 mm (0.79 to 3.94 in.), particle lengths which are generally above our observations. The response was nonlinear, and the effect of chop length diminished with longer chop lengths. Overall, studies looking directly at the effects of particle length have shown some reduced density with increasing particle length whereas our survey and that of Ruppel et al. (1995) have shown little effect. These results suggest the cross correlations observed in our survey may have masked the effects of particle size. Even so, it would appear the effect of particle size on density is relatively small.

Finally, the results of our survey suggest the use of dual wheels on the packing tractor, either on the rear or both front and rear, does not adversely affect DM density. This is certainly at odds with common guidelines to farmers today, which emphasize single-wheeled tractors, as well as with the results of the study by Laue (1990). The reason for this discrepancy is not clear. However, Laue's model silos with an 80-cm (31.5 in.) depth may be more representative of what occurs at the top of the silo whereas our measurements were typically 2 m (7 ft) or more below the top.

Factors Affecting Compaction in Other Media

The consolidation of forages has received relatively little attention compared to the compaction of other media. Soil compaction in particular has been studied because of the effects of machinery on rutting of soils, loss of infiltration capacity and soil structure, and adverse effects on crop yields as well as on densification for increased soil strength for roads and driveways. Reviews by Hadas (1994) and Håkansson and Reeder (1994) summarize research on soil compaction effects in both the plow layer and the subsoil.

Soehne's (1953) theory has been the primary basis for comparison with experimental data. By this theory, stress in topsoil depends on contact stress whereas stress in the subsoil is determined by load. Thus in topsoil (Hadas, 1994), a given contact stress (load divided by contact area) should penetrate deeper into the soil as the wheel contact area increases (and the load increases). Conversely for a given axle load, changing from single wheels to dual wheels reduces contact stress and the depth of soil affected by the stress. For a given contact area, increasing load increases the stress at a specific soil depth and the depth to which stresses penetrate into the soil. In subsoil, theory indicates contact area has no effect on stress, and stress is primarily affected by axle load.

The theory predicts soil stresses reasonably in homogeneous soils under static loads (Hadas, 1994) and in general the depth of measurable soil compaction increases with increasing axle load (Håkansson and Reeder, 1994). However, the theories may not be as accurate under dynamic loading and repeated cycles of soil compaction (Hadas, 1994). Wolf and Hadas (1984) found wheeled and tracked tractors of the same weight (but the contact time and pressure of the tracked tractor was four times and one fourth, respectively, that of the wheeled tractor) produced similar levels of soil compaction. These results suggest total stress energy (load multiplied by number of passes multiplied by pass dwelling time) determines the amount of soil compaction. Various studies as summarized by Hadas (1994) and Håkansson and Reeder (1994) have found soil compaction increases linearly with the logarithm of the number of passes or compressions.

Guidelines for landfill compaction list layer thickness and the number of passes as being the two key factors for high density (Caterpillar, 1994). Density drops sigmoidally with increasing depth of material, with density of refuse at a 1.0 m (3.3 ft) initial depth producing less than half the density of refuse spread at 0.5 m (1.6 ft). Similar to the soil work, increasing the number of passes increases density at a decreasing rate so little improvement in density occurs after 5 to 6 passes.

Overall, these results indicate some similarities to ours. The median distance below the surface for the cores taken in our study was 2.16 m (7.09 ft). Thus the lack of effect of the number of tires per tractor or tire pressure in our study appears similar to that observed in the subsoil where axle load rather than contact pressure is important. Perhaps the effect of number of tires and/or tire pressure may have been important if we had sampled the densities at the tops of the silos. The effect of the number of passes (logarithm) is similar to the effect of time per tonne (square root) in our study (i.e., a smaller increase in density with each additional unit of packing as shown in fig. 6). Using the logarithm creates a mathematical problem in dealing with those instances where no packing is done. Other fractional powers of packing time per tonne were investigated but did not significantly improve the coefficient of determination.

Finally, the effects of layer thickness in refuse compaction are similar in magnitude to the effects observed in our study although the range of depths in our study was much narrower.

LIMITS OF THE STUDY

While the parameters in the packing factor do appear reasonable based on other compaction research, there are caveats with the approach used in our study. First, as discussed above regarding particle size, cross correlations between factors may have influenced the importance of a particular factor. This should have been minimized by our large sampling size relative to previous studies but still could be important. Thus research to verify the importance of the various factors is needed.

Second, we relied on farmer estimates of most factors, which could introduce substantial error. For some factors like tractor weight we often had both tractor models as well as estimated or measured tractor weights so there were means of corroborating values. Other factors such as layer thickness relied completely on the farmers' estimates and are subject to error. Consequently, the low coefficient of determination for our packing factor in relation to adjusted DM density may be due largely to variability in farmers' estimates of various factors rather than missing a significant factor.

Third, because sampling was well below the surface, the results of the study may not reflect the factors affecting the density in the top 30 to 50 cm (12 to 20 in.). At the top, tire pressure, use of dual wheels, etc. may be more important factors based on soil compaction research. Certainly there is a need to investigate the variation in density with distance below the top surface and to ascertain that densities at the top of the silo are affected similarly by various packing factors to those lower in the profile.

PREDICTION EQUATION FOR SILAGE DENSITY

Using equations 1 and 2 and the equation in figure 5, one can estimate silage density in a bunker silo based on height and the various packing factors. Equation 1 integrated over typical bunker silo heights (2 to 8 m; 6 to 26 ft) results in average densities increasing at nearly a linear rate with height ($r^2 > 0.998$). Also in this range of silo heights, the ratio of the average density for a given height to the density at 2.16 m (7.09 ft) does not vary by more than ± 5% over a reasonable range of wet densities at the top of the silo, γ_o, (300 to 700 kg/m^3; 19 to 44 lbs/ft^3). Using the average calculated γ_o for this study (540 kg/m^3; 34 lbs/ft^3) and converting the relative densities with height to a linear function, average bunker silo DM density as a function of packing and height is:

$$\rho = (136.3 + 0.042P) \cdot (0.818 + 0.0446H) \quad \text{SI} \quad (4a)$$

$$\rho = (8.5 + 0.0155P) \cdot (0.818 + 0.0136H) \quad \text{Customary} \quad (4b)$$

where

ρ = average bunker silo DM density, kg DM/m^3 (lbs DM/ft^3)

H = silage height, m (ft)

P = packing factor, kg (h·g/t·kg)$^{1/2}$ cm^{-1} [lbs (h/T)$^{1/2}$ in.$^{-1}$]

The standard errors of prediction are 59.9 kg DM/m^3 and 3.70 lbs DM/ft^3, respectively. While the standard error is sufficiently large to preclude an accurate prediction of density, this equation may be useful for estimating how changes to various packing procedures affect density. An Excel® spreadsheet has been developed incorporating this equation so farmers and farm consultants can evaluate current packing practices and determine practical means of improving density for their particular conditions. This spreadsheet listed as the Bunker Silo Density Calculator is available from the following Internet site:

http://www.uwex.edu/ces/crops/uwforage/storage.htm

CONCLUSIONS

Our survey of bunker silos found a wide range of dry matter densities (106 to 434 kg/m^3; 6.6 to 27.1 lbs/ft^3), some typical of densities in tower silos. Densities were higher in deeper silos and that effect could be explained by equations of self-compaction developed for tower silos. Other factors most strongly correlated with dry matter density included initial layer thickness, average packing tractor weight, packing time per tonne as-fed and dry matter content. These four factors were combined into a packing factor [W (TD)$^{1/2}$ L^{-1}] that explained 18.2% of the variation in dry matter density. Additional factors such as the use of dual wheels did not significantly improve the prediction of dry matter density.

Because this study was a survey, the strong correlations observed do not necessarily imply cause and effect. While the factors found to be important are supported particularly by research in other similar fields, more research is needed to (1) confirm these factors as important in packing bunker silos, and (2) determine if densities at the tops of bunker silos are affected by these or other factors.

ACKNOWLEDGMENTS. The authors would like to acknowledge the invaluable assistance of the county extension agents involved in taking core samples and surveying the farmers: K. Bolton, R. Cropp, L. Cunningham, C. Duley, M. Glewen, S. Hendrickson, R. Kaiser, J. Keuning, J. Key, R. Knapp, J. Leverich, Z. Miller, L. Milligan, D. O'Neil, I. Possin, D. Sutter, R. Tigner, D. Wachter, and M. Wildeck. The electric generators that made sampling at bunker faces possible were provided by Weiser Concrete, Inc. The authors are also grateful for the technical assistance of A. Dean and help in processing samples from A. Hable, S. Lennix, and R. Troncoso. Finally, the authors are appreciative of the many farmers who participated in the study and made it possible.

REFERENCES

ASAE Standards, 45th Ed. 1998. St. Joseph, Mich.: ASAE.

Caterpillar, Inc. 1994. *Caterpillar Performance Handbook*, 25th Ed. Peoria, Ill.: Caterpillar.

Darby, D. E., and J. C. Jofriet. 1993. Density of silage in horizontal silos. *Canadian Agric. Eng.* 35(4): 275-280.

Hadas, A. 1994. Soil compaction caused by high axle loads—Review of concepts and experimental data. *Soil Tillage Res.* 29(2-3): 253-276.

Håkansson, I., and R. C. Reeder. 1994. Subsoil compaction by vehicles with high axle load—Extent, persistence and crop response. *Soil Tillage Res.* 29(2-3): 277-304.

Honig, H. 1991. Reducing losses during storage and unloading of silage. In *Forage Conservation Towards 2000*, eds. G. Pahlow, and H. Honig, 116-128. Sonderheft 123. Braunschweig, Germany: Landbauforschung Völkenrode.

Jofriet, J. C., and Q. Zhao. 1990. Design load recommendations for bunker silo walls. ASAE Paper No. 90-4542. St. Joseph, Mich.: ASAE.

Laue, A. 1990. Zur Problematik der dynamischen Verdichtung von Anwelkgras im Fahrsilo (Analysis of dynamic compression of wilted grass in horizontal silos). Diplomarbeit Kiel, Germany, 1-132.

McGechan, M. B. 1990. A review of losses arising during conservation of grass forage: Part 2, Storage losses. *J. Agric. Eng. Res.* 45(1): 1-30.

Pitt, R. E. 1983. Mathematical prediction of density and temperature of ensiled forage. *Transactions of the ASAE* 26(5): 1522-1527, 1532.

Pitt, R. E., and K. G. Gebremedhin. 1989. Effects of forage species, chop length, moisture content, and harvest number on tower silo capacity and wall loads. *J. Agric. Eng. Res.* 44(3): 205-215.

Ruppel, K. A., R. E. Pitt, L. E. Chase, and D. M. Dalton. 1995. Bunker silo management and its relationship to forage preservation on dairy farms. *J. Dairy Sci.* 78(1): 141-153.

Shinners, K. J., R. E. Muck, R. G. Koegel, and R. J. Straub. 1994. Silage characteristics as affected by length-of-cut. ASAE Paper No. 94-1524. St. Joseph, Mich.: ASAE.

Soehne, W. H. 1953. Pressure distribution in the soil and soil deformation under tractor tyres. *Grund. Landtech.* 5(1): 49-63.

Wolf, D., and A. Hadas. 1984. Soil compaction effects on cotton emergence. *Transactions of the ASAE* 27(3): 655-659.