Bunker Silo Management and Its Relationship to Forage Preservation on Dairy Farms

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ABSTRACT

Management practices were quantified for ensiling of alfalfa and grass crops in 30 fillings of 15 bunker silos over 2 yr on 12 farms in eastern New York. Wet mass ensiled per day, time and vehicle weight in packing, DM and nutrient analyses, and particle size were determined at filling. At feedout, cover integrity, density of tires used to hold down the cover, smoothness of the working face, and feedout rate were assessed. Rate and extent of DM loss, nutrient content of ensiled material, silage temperatures at the working and top surfaces, and aerobic instability were evaluated. Packing intensity, defined as the vehicle weight multiplied by the time spent packing per unit of top surface area, was associated with increased silage DM density, lower DM losses, and improved aerobic stability. The ADIN was lower with filling periods <10 d, higher density of tire placement, and increased smoothness of the working face. Silos filled by formation of angled wedges had lower increases in ADF during ensiling than did silos filled by formation of horizontal or vertical layers. Silos with linear feedout rates >11.6 cm/d averaged nearly 10 percentage points lower in extent of DM losses.

(**Key words**: bunker silo, management, silage, preservation)

Abbreviation key: **NSC** = nonstructural carbohydrates, **SP** = soluble protein.

INTRODUCTION

Loss of forage DM and deterioration of quality are often associated with silage storage systems (10). Reported losses vary from 3 to 25% but potentially reach 70%; the losses are concentrated in the digestible carbohydrate fraction (11). Up to 50% of forage protein may be solubilized to nonprotein forms in the silo, and indigestible Maillard products may be formed from excessive heating (24). Losses and quality changes are typically considered to be more extreme in bunker silos than in tower silos because of greater surface area for oxygen penetration, less perfect sealing, and greater dependence on management practices during filling and feedout (1, 9). Optimal management of commercially sized and operated bunker silos for storage of legume and grass forage crops has not been adequately described for US farms.

The objectives of this study were to quantify management practices associated with storage of alfalfa and grass in bunker silos on a set of farms in eastern New York and to correlate these practices with measured assessments of forage preservation in these silos.

MATERIALS AND METHODS

Farm Variables

Twelve farms in Washington County, New York participated in the study. Data were collected from 30 separate silo fillings in 15 bunker silos over 2 yr. Listed in Table 1 are the herd sizes, milk production, crop areas of alfalfa and grass, and sizes and wall characteristics of bunker silos in the study. Farm selection was based primarily on the willingness of the farm manager to collect weather data and silage samples and to cooperate in recovery of buried bags. Farms had herd sizes of 59 to 337 cows and milk production from 7400 to 9920 kg/yr per cow. Mean alfalfa ADF at harvest over the 2-yr study, 1990 and 1991,

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TABLE 1. Farm sizes, milk production, average forage ADF, and silo sizes for cooperating farms in the study.

Cows	Milk production	Forage crop area	Forage ADF	Silo	Length	Width	Height	Wall type[1]
(no.)	(kg/yr per cow)	(ha)	(% of DM)	(no.)		(m)		
165	8980	110	31.4	1	40	11	4	CIP
76	8300	38	35.2	2	34	9	3	PTU
337	9920	105	31.5	3	66	14	4	CIP
				20	13	7	3	CIP and FOR
74	9130	40	36.9	4	31	10	3	CIP and FOR
120	7480	81	35.2	5	27	9	3	PTU
				6	40	12	2	SOIL
67	8980	20	33.5	7	38	8	3	PRE and SOIL
67	7400	41	38.0	8	31	7	2	SOIL and FOR
229	9900	116	28.4	10	32	10	3	PTU
301	8770	113	31.3	11	37	9	3	PTU
61	8570	31	38.6	13	27	11	2	PTU
59	8280	28	38.0	14	23	6	3	PRE
156	9120	101	33.0	15	61	6	3	PRE
				19	32	6	3	PRE

[1] CIP = Concrete, cast in place; PRE = precast concrete; PTU = concrete, poured tip up; SOIL = earthen; FOR = some walls formed by other forage.

was 34.3% for all farms and varied among farms from 28 to 39%. This variation indicated a range in capacity to harvest forage at optimal maturity. Silos varied in size by a factor of 10 and in configuration (ratios of width to length and width to height) by a factor of 5.

Variables for Silo Management

Management data were obtained through logs kept by cooperators and through information recorded by researchers during silo filling and feedout.

Cooperator Logs. Cooperators recorded dates of silo fillings, daily maximum and minimum temperatures and precipitation during filling, wet mass of loads, number of forage loads each day, time spent packing, and vehicle used for packing. Cooperators also estimated the percentage of legume in the forage. Silage density was later estimated from the total mass of forage placed in the silo divided by the volume of the silage stack.

Filling Variables. Filling method was categorized as one of three types: 1) full height, in which the total silo height was maintained as length was increased; 2) full length, in which the total silo length was maintained as height was increased; and 3) progressive wedge, in which loads were added with a slope of 20 to 30° as length and height were increased simultaneously.

For determination of DM, single grab samples (100 to 200 g) were removed from each load and analyzed with a Koster Crop Tester (Koster Crop Tester, Inc., Cleveland, OH). Particle sizes were estimated by sifting ≥300 g (20 to 80 g at a time) through two successive wire trays (20 × 36 cm wide × 2.5 cm deep) with square opening dimensions of 12.7 and 6.35 mm, respectively. According to the overbalancing principle of Vaage et al. (23), these opening dimensions permit passage of particles with lengths ≤36 and 18 mm for the coarse and fine screens, respectively. The pan was held flat to within about 10 degrees of horizontal, and one side was tapped repeatedly until most of the silage had migrated to the lower side; this procedure was repeated three to eight times. The percentage of wet weight retained on each screen was recorded. A weighted score (1.0 = finest category to 3.0 = coarsest category) was calculated for each sample.

Intensity of packing was quantified in two ways. Tractor mass (tonnes) was considered to be a factor in packing. Time spent packing (hours) was divided by the mass of forage ensiled (tonnes) or by the top surface area of the silo (square meters). Multiplication of tractor mass by time spent packing per area or per mass gave two measures of packing intensity (hour·tonnes per tonne or hour·tonnes per square meter). With one exception (silo 8), all packing vehicles were wheeled.

Feedout Variables. Feedout evaluations were made ≥10 d ($\bar{X}$ = 107) after the completion of silo filling. All silos were covered with plastic. Sealing condition was gauged at feedout using visual assessments of the incidence of tears or holes, gaps between sheets, plastic thickness, and plastic integrity. The rating system was 1.0 = poor condition to 3.0 = excellent condition; ratings were made to .1 point. Density of tire placement on the top surface was determined from the number of tires per area.

Linear feedout rate of the working face (centimeters per day) was estimated by marking successive locations of the face over ≥4 d ($\bar{X}$ = 14). Face condition was rated from 1.0 = poor face condition, high unevenness at the edges, evidence of lifting to dislodge silage, or large amounts of loose material piled at the base, to 3.0 = excellent face condition, little unevenness, tightness of layers in the silage, or minimal loose silage at the base. Ratings were made to .1 point.

Preservation Variables

Silage Losses and Temperatures. Buried bags were used to measure the rate and extent of DM loss. In 1990, 7 to 12 ($\bar{X}$ = 10) nylon bags (25 × 50 cm) were buried in each silo during filling. Bags were evenly distributed over the length and width of the silo and buried approximately 1 m below the surface. Dry mass per bag ranged from .16 to .32 kg ($\bar{X}$ = .23 kg). In 1991, 3 to 5 ($\bar{X}$ = 4.75) nylon bags (60 × 110 cm) were buried in each silo along a line crossing the silo width at about 5 m from the feedout end. Each bag contained 1.4 to 3.2 kg of DM ($\bar{X}$ = 2.1). Orange ribbons attached to each bag were used to mark the locations; bags were recovered in 23 of the 30 silo fillings. Mean burial times were ≤60 d in 13 of the 23 recoveries, and 3 of the recoveries had burial times of nearly 300 d. Initial and final wet masses in each bag were determined with a spring scale (Model 40; Hanson Scale Co., Shubuta, MS) that was accurate to .025 kg. Initial and final DM contents were determined with a Koster Crop Tester. Rate of DM loss (percentage per month) for each bag was obtained by dividing the DM loss by the storage period. Means for all bags were used to characterize each silo.

A test of aerobic instability of the silage was performed during feedout by placing 6 to 9 kg of wet mass from the mixed samples from the working face into a styrofoam container (20 × 33 cm wide and 30 cm high). The container was stored indoors, and silage and ambient temperatures were recorded at 0, 12, 24, 48, 72, 96, and 120 h. Temperatures were recorded with a 20-cm probe thermometer (Taylor Bi-Therm; Thermometer Corp. of America, Fletcher, NC) inserted fully into the silage. Aerobic instability was calculated as the rate of temperature rise using the maximum recorded temperature divided by the time to reach maximum temperature.

Temperatures within the stored silage were measured during feedout at 20-cm depths into the working face and under the top cover. Measurements were taken at 12 locations across the working face at three elevations from 13 cm above the base to 13 cm below the top surface. Four measurements were taken across the top surface along a diagonal line between two corners, coming no closer than 1 m from any edge. Ambient temperatures were recorded at the same time.

Nutrient Analysis. Forage analysis was performed on grab samples from loads during filling and from the exposed face during feedout. Load samples from each day during filling were mixed at the end of the day, and a subsample of 170 to 280 g was frozen at –19°C. About 175 g of frozen material were sent to a commercial laboratory (Northeast DHIA, Ithaca, NY) and analyzed, using wet chemistry, for concentrations of DM, ADIN, soluble protein (SP), ammonia N, and pH. Samples were analyzed using near infrared spectroscopy for NDF, ADF, CP, and minerals. Additionally, approximately 120 ml of tap water (pH 6.8 to 7.2) were mixed with 80 g of forage, and an electronic probe (Omega PHH-

1; Singapore) was used to measure pH. Field and laboratory measurements of DM content were correlated (r = .964; proportionality = .949.

At feedout, samples were taken from the 12 locations across the working face where temperatures were measured. A 15-cm keyhole saw was used to remove a section of silage (10 × 10 × 13 cm) at each location (total of 8 to 11 kg of wet mass). Samples were mixed, and three 300-g subsamples were placed on ice and sent for analysis to the commercial laboratory.

Statistical Analyses

Initially, ranges and frequency distributions of each management and preservation variable were examined. Simple linear regressions for two parameters were performed to relate individual management factors and individual preservation variables. An ANOVA of the regression and correlation coefficient were used to indicate significance of the relationships. Because the data were not from controlled experiments, many measured variables could not be assumed to be statistically independent. Thus, few relationships were expected to attain significance ($P < .05$), and conclusions about causal relationships could not be drawn. Further analyses were performed in which silo fillings were grouped into three ranges according to the distribution of the values of each management variable. These ranges corresponded to the lowest 25% of the distribution, the middle 50% of the distribution, and the highest 25% of the distribution. A one-way ANOVA was then performed on preservation variables among the three groups. This process of grouping and ANOVA was repeated for each management variable. All statistical evaluations were performed using Minitab Release 8.2 (15).

RESULTS

Farm Observations

Filling Variables. Ranges and means for rate of filling, duration of the filling period, packing per mass and per area, particle size, and forage DM are given in Table 2. Days in the filling period varied by a factor of 10 (3 to 32 d); the mean filling period was 9 d. One farm (silo number 8, Table 1) was responsible for the longest filling periods, 30 and 32 d. There was no delay in filling in 8 of 30 silo fillings; the mean delay was 23.7% of the filling period. Number of filling days bore no significant relationship to the total wet mass of forage ensiled (P = .140), which concurred with the strong correlation between harvesting rate and quantity of DM stored (r = .685; $P <$ .001). Thus, farms with larger silos were equipped to harvest forage more quickly so that duration of the filling period was distributed fairly evenly across silo sizes.

Packing vehicle masses ranged from 3.4 to 16.8 tonne. Packing per area or per mass varied by factors of 8 to 12. Less than 2 min of packing time per wet tonne harvested was spent in 7 of 30 silos; in 5 silos, >6 min/tonne were spent packing.

Particle size score had a range of .67 units and was quite variable, considering that all forage harvesters in this study were set at .9525-cm theoretical length of cut. In 16 silo fillings, >40% of the forage sample passed

TABLE 2. Ranges and means in silo management variables measured during filling.

	Filling rate	Filling period	Packing per mass	Packing per area	Forage particle size[1]	Forage DM
	(tonne/d)	(d)	(h·tonne per tonne)	(h·tonne per m^2)		(%)
$\overline{X}$	16.0	9.3	.480	.578	1.85	38.5
Minimum	3.9	3.0	.151	.137	1.48	25.9
Maximum	49.4	32.0	1.233	1.740	2.15	54.6
SD	10.6	6.9	.268	.423	.19	7.2

[1] Range of 1.0 = fine to 3.0 = coarse.

through the fine screen; in 3 silo fillings, >40% was of medium coarseness; and, in 2 silo fillings, >40% was retained on the coarse screen. Particle lengths of a single sample were measured by hand for a silo filling for which particle size score was 1.645, in the lowest 25th percentile. Of the 168 particles measured, 80.2% had lengths >.762 cm, which is the minimum length to stimulate rumination according to Shaver et al. (22). Median particle length was 2.9 cm. Thus, even for this relatively fine sample, particle lengths were reasonably long.

The DM content at ensiling varied by nearly 30 percentage points. In initial analysis, the relationship between DM content and average ambient temperature during filling was highly significant ($r = .58$; $P = .001$); the equation was

$$\text{DM } (\%) = 12.9 + 1.28(T)$$

where T = mean ambient temperature (degrees Celsius) during filling. Wilting period in this study was <.5 d in 44% of silo fillings. Thus, attempts by farm managers to control DM content were at least partially thwarted by weather conditions; warmer weather was associated with drier forage at ensiling. Silage effluent was produced in 7 silo fillings, all of which had a DM content <32%. Quantity of effluent was substantial in silo number 1, which had a DM content of 23.2%. Four silos without effluent had DM content between 26 and 30%.

Feedout Variables. Ranges and means for linear feedout rate, rating of face condition, covering condition, and silage density are given in Table 3. Linear feedout rate varied by about eightfold. The mean of 19.4 cm/d exceeds the recommended minimum rate of 15 cm/d in summer (16). In 5 silos, feedout rate was <10 cm/d.

Bucket unloaders were the predominant method of silage removal. For 3 silo fillings on one farm (silo numbers 3 and 20), a block-cutting attachment of hydraulically operated knives was used. Face condition ratings for these silo fillings were 3.0, 2.8, and 1.5 and, thus, were not consistently higher than the mean rating of about 2.0. Face condition ratings were evenly distributed: 8 fillings rated 2.0, 11 rated >2.0, and 10 rated <2.0.

Visual ratings of cover condition were fairly high; only 3 ratings were <2.0, and 5 ratings were 3.0. All silos were covered within 2 d of the end of filling. The percentage of top surface area covered at feedout ranged from 47 to 100%; only 2 silos had <65% coverage. Tire density ranged widely (Table 3): >2.3 tires/m^2 in 7 silos, and <1.2 tires/m^2 in 12 silos. Tire density was similar within silo fillings on the same farm, suggesting that farm policy determined density of tires.

Losses and Temperatures. Ranges and means in silo DM losses, rates of DM losses, temperatures, and aerobic instabilities are given in Table 4. In 5 of the 23 silos in which bags were recovered, DM loss was slightly negative. Mean burial time for all silos was 96 d; losses averaged about 8%. Rates of loss, which should be more consistent across burial times, averaged about 3.5%/mo. However, bags that were buried for shorter times actually had higher rates of loss, which is consistent with a high rate of loss in the early aerobic phase of ensiling (11).

TABLE 3. Ranges and means in silo management variables measured during feedout.

	Linear feedout rate	Face condition score[1]	Cover condition score[2]	Tire density	Silage DM density
	(cm/d)			(tires/m^2)	(kg/m^3)
$\overline{X}$	19.4	1.99	2.40	1.40	236.9
Minimum	5.5	.5	1.0	.11	100.9
Maximum	42.4	3.0	3.0	3.66	376.5
SD	8.5	.69	.58	.86	68.7

[1] Range of 1.0 = rough to 3.0 = smooth.

[2] Range of 1.0 = poor condition to 3.0 = excellent condition.

TABLE 4. Ranges and means in silage losses and temperatures.

	DM Loss	Rate of DM loss	Top silage temperature rise	Face silage temperature rise	Aerobic instability
	(%)	(%/mo)	(°C)		(°C/d)
$\overline{X}$	7.95	3.54	9.9	11.2	5.52
Minimum	−2.70	−3.03	.6	1.3	0
Maximum	43.0	22.6	26.7	34.4	28.8
SD	11.07	5.16	7.9	7.5	6.72

Silage temperatures at the working face exceeded 32°C in 16 silos and 41°C in 6 silos; temperatures were <24°C in 4 silos. Mean temperature for all silos was 34°C, which was about 10°C above ambient temperature on average. The difference between silage and ambient temperatures was poorly correlated with ambient temperature ($r = .202$, $P > .15$ at face; $r = 0$, $P = .454$ at top). Silage temperatures above ambient were used as an index of heating and were similar at the top and working face surfaces, although temperatures were highest at the face. In a silo that was associated with extreme aerobic deterioration (silo number 8), temperatures were 34°C above ambient.

Tests of aerobic instability yielded a mean temperature rise of 5.5°C/d. No heating occurred in silage from 8 silo fillings. Nine of the silage samples were clustered at near 7°C/d, and 3 silage samples exhibited rates >13.4°C/d.

Nutrient Concentrations. The percentage of legume estimated by the farm managers varied from 0 to 95%; mean was 60% (SD = 26.8). Analysis of Ca content showed a strong relationship to percentage of legume ($r = .740$; $P < .001$); the empirical equation was

$$\text{Ca } (\%) = .682 + .00730(\text{legume}) \ (\%).$$

The high significance of this relationship suggests that the estimation of percentage of legume by farm managers was reasonable.

Data in Table 5 summarize the changes in concentrations of ADF, ADIN, and nonstructural carbohydrates (NSC) during storage and the measurements of SP, ammonia N, and pH of silage collected from the working face. Analysis of the preensiled forage strongly indicated the occurrence of biological activity during transport to the laboratory. Specifically, pH decreased significantly ($P < .05$) between the field and laboratory determinations from a mean of 5.90 to 4.90. Thus, initial pH and concentrations of SP and ADIN were not considered to be representative of the forage at ensiling.

Mean increase in ADF was >3 percentage points during storage; in three tests, ADF decreased slightly (Table 5). Change in NSC concentration ranged widely, but, on average, was near zero. Final ADIN in the silage averaged about 10% of total N but varied widely; ADIN in one silo was 45%. Concentrations of SP were about 50% on average but also varied

TABLE 5. Ranges and means in silage nutrient concentrations.

	ΔADF[1]	ΔNSC[2]	ADIN	Soluble protein	NH_3 N	pH
	(% of DM)	(% of CHO)	(% of total N)	(% of CP)	(% of total N)	
$\overline{X}$	3.21	.29	9.78	51.62	7.27	4.82
Minimum	−2.70	−11.60	3.64	14.55	1.67	4.20
Maximum	8.70	12.80	44.55	66.82	17.54	8.60
SD	2.76	6.79	7.81	10.98	3.85	.76

[1] Change in ADF during storage.

[2] Change in nonstructural carbohydrates during storage.

widely. A strong negative correlation existed between ADIN and SP (r = –.88; $P < .001$); the empirical relationship was

$$SP = 6.38 - 1.24(ADIN)$$

where SP = percentage of CP, and ADIN = percentage of total N. This relationship is expected because Maillard products are formed from compounds within the SP fraction (24). Thus, lower SP and higher ADIN were apparently correlated through the occurrence of browning reactions. Ammonia N averaged about 7% of total N; 14 silo fillings had <6%, and 4 fillings had >12%.

Silage pH ranged widely, but most were closely distributed about the mean pH of 4.8. Unlike the forage pH at filling, a paired *t* test showed no significant difference ($P = .384$) between field and laboratory determinations of silage pH. One silo filling (silo number 8) showed a high pH of 8.6 and was associated with severe aerobic deterioration. In 7 silo fillings, pH was >5.

Correlation and Regression Analyses

Filling Variables and Silage Losses and Temperatures. Density of silage was significantly related to packing intensity in hour·tonnes per square meter (r = .526; $P = .007$). Silage density was not significantly correlated with DM content (r = –.20; $P = .176$) or stack height ($P = .258$), even though stack height and packing per area were positively correlated (r = .37; $P = .040$). Density was also not significantly related to NDF concentration ($P = .443$) or particle size ($P = .670$). Figure 1 shows the relationship between density and packing intensity; the empirical relationship was

$$\text{density} = 189 + 83.61(P_{\text{area}})$$

where density = DM density (kilograms per cubic meter), and P_{area} = packing per area (hour·tonnes per square meter). According to the equation, silo DM capacities were increased by 60% as packing intensity increased either by increases in the time spent packing per area or by use of heavier equipment. The two silo fillings that used a track vehicle were close to the regression line in Figure 1.

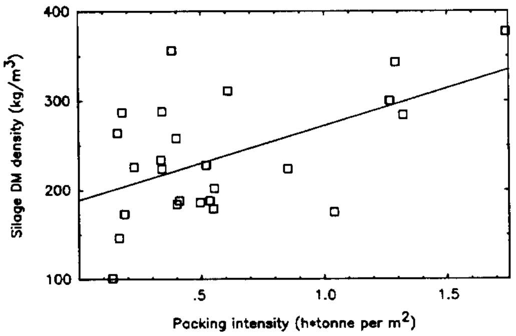

Figure 1. Data (□) and fitted line (—) showing the relationship between silage DM density and packing intensity (r = .493; $P = .007$).

Extent of DM loss was not significantly correlated with silage density (r = –.07; $P = .105$). The DM loss was reduced by 2.2 percentage points for every increase of 50 kg/m^3 in density, which was associated with more intensive packing.

The matrix of correlation coefficients between management variables at filling and silage DM losses, temperatures, and aerobic instability are shown in Table 6. Packing per mass or per area was positively correlated with silage temperatures at the top surface; packing per area was negatively correlated with aerobic instability. Thus, greater packing intensity was associated with higher temperature rises above ambient at the top surface but better aerobic stability at the working face. The empirical equation relating aerobic instability and packing per mass was

$$AI = 9.31 - 7.53(P_{\text{mass}})$$

where AI = aerobic instability (Celsius degrees per day), and P_{mass} = packing per unit mass (hour·tonnes per tonne).

Larger particle size was associated with significantly lower temperature rises at the top surface. Lower forage DM content was associated with significantly lower temperatures at the working face and significantly lower rates of DM loss in the buried bags (Table 6). The empirical relationship between rate of DM loss and DM content was

$$\text{loss rate} = -10.26 + .357(DM)\ (\%)$$

TABLE 6. Correlation coefficients between silo management variables measured during filling and silage losses and temperatures.

	Filling rate	Filling period	Packing per mass	Packing per area	Forage particle size	Forage DM
DM Loss	0	.11	0	0	0	0
Rate of DM loss	0	–.21	0	0	.27	.45*
Top silage temperature	.16	0	.39*	.32*	–.29†	.16
Face silage temperature	0	.13	.17	0	–.14	.30†
Aerobic instability	0	0	–.26†	0	0	–.15

†$P < .10$.

*$P < .05$.

where loss rate = percentage rate of DM loss, per month.

Filling Variables and Nutrient Analyses. Table 7 shows the matrix of correlation coefficients between management variables at filling and nutrient analyses at feedout. Filling period showed the strongest correlations; longer filling periods were associated with larger increases in ADF, higher ADIN, and higher silage pH. Shorter filling periods should have reduced time of exposure to oxygen during filling and were associated with better preservation.

Packing per mass or per area had no significant correlation with nutrient concentrations (Table 7). However, particle size, for which the scale increases as coarseness increases, was positively correlated with change in ADF and negatively correlated with SP. The empirical relationship between change in ADF and particle size score was

$$\Delta ADF = -9.18 + 6.70(PS)$$

where ΔADF = change in ADF during ensiling (percentage of DM); and PS = weighted mean particle size score (range of 1 to 3). Smaller changes in ADF may be the result of lower losses of non-ADF material in ensiling, although particle size was not significantly correlated with DM loss (Table 6). Even though smaller particle size was associated with better preservation, it can also depress rumination in dairy cows (7).

The relationship between DM content and silage pH was not significant ($P > .05$). Given

TABLE 7. Correlation coefficients between silo management variables measured during filling and silage nutrient concentrations.

	Filling rate	Filling period	Packing per mass	Packing per area	Forage particle size	Forage DM
ΔADF[1]	0	.32*	0	0	.42**	0
ΔNSC[2]	0	0	0	.26	0	0
ADIN	–.32*	.74**	0	0	.13	0
Soluble protein	.24	–.68**	0	0	–.31†	0
Ammonia N	.23	0	0	0	0	–.15
pH	–.10	.54**	0	0	0	0

[1] Change in ADF during storage.

[2] Change in nonstructural carbohydrates during storage.

†$P < .10$.

*$P < .05$.

**$P < .01$.

TABLE 8. Correlation coefficients between silo management variables measured during feedout and silage losses and temperatures.

	Linear feedout rate	Face condition score	Cover condition score	Tire density	Silage DM density
DM Loss	0	–.17	0	–.16	–.07
Rate of DM loss	0	0	0	0	0
Top silage temperature	.18	0	$-.30^{*}$	$-.35^{*}$	0
Face silage temperature	0	0	0	0	0
Aerobic instability	0	–.11	.11	0	0

$^{*}P < .05$.

that losses and temperatures were reduced at lower DM, pH should have decreased as DM decreased (24). However, the silo filling associated with extensive aerobic deterioration (silo number 8) had a pH of 8.6 and a DM of 25.9%. When this data point was removed, the relationship became significant (r = .35; $P = .037$). The empirical equation was

$$\text{pH} = 4.18 + .0134(\text{DM})\ (\%)$$

where pH = final silage pH.

Feedout Variables and Silage Losses and Temperatures. The matrix of correlation coefficients between management variables at feedout and silage DM losses and temperatures is given in Table 8. Only two correlations were significant between top surface temperature and cover condition and between top surface temperature and tire density. Variation in the spacing between tires accounted for about 12% of the observed variation in temperature rise from 0 to about 27°C. The empirical equation was

$$\Delta T_{\text{top}} = 14.7 - 3.375(\text{tire density})$$

where ΔT_{top} = temperature rise (degrees Celsius) above ambient at 20 cm below the top surface, and tire density = number of tires per square meter.

Feedout Variables and Nutrient Analyses. Table 9 shows the matrix of correlation coefficients between management variables assessed at feedout and silage nutrient analyses. Face condition score and tire density were related to nutrient preservation. Better condition of the working face was associated with lower ADIN. The empirical relationship was

$$\text{ADIN} = 19.5 - 4.81(\text{face})$$

TABLE 9. Correlation coefficients between silo management variables measured during feedout and silage nutrient concentrations.

	Linear feedout rate	Face condition score	Cover condition score	Tire density	Silage DM density
ΔADF[1]	0	0	0	0	0
ΔNSC[2]	0	0	0	0	0
ADIN	–.10	$-.39^{*}$	0	$-.36^{*}$	0
Soluble protein	0	$.37^{*}$	0	$.31^{\dagger}$	0
Ammonia N	–.17	$.28^{\dagger}$	0	0	0
pH	–.05	–.19	0	0	0

[1] Change in ADF during storage.

[2] Change in nonstructural carbohydrates during storage.

$^{\dagger}P < .10$.

$^{*}P < .05$.

where ADIN = percentage of total N; and face = face condition score (1 = rough to 3 = smooth). This relationship suggests that heat damage and rise in ADIN occurred during feedout. Hence, ADIN increases may have been limited by maintenance of a smoother working face that reduced oxygen infiltration. Face condition was also correlated with lower SP, which is consistent with the negative relation between ADIN and SP. Changes in ADF and NSC during ensiling were not related to face condition, implying that these changes occurred during the early or middle phases of ensiling.

Greater tire density was associated with significantly lower ADIN, which is consistent with the relation between tire density and silage temperature at the top surface. The empirical equation was

$$\text{ADIN} = 15.0 - 3.530(\text{tire density})$$

where ADIN = percentage of total N, and tire density = number of tires per square meter. Apparently, infiltration of air under the top cover was reduced as more tires were used as weights. Cover condition had no effect on nutrient analyses, probably because of the high ratings of cover conditions for all silos.

Although higher linear feedout rate was associated, on average, with lower ADIN, lower ammonia N, and lower silage pH, none of these relationships was significant. Given that average feedout rate for all silos was fairly high at 19.4 cm/d (Table 3) and that few silos were <10 cm/d, the relationship might have been significant if more silos had had low feedout rates.

Environmental Variables. Although beyond the control of farm managers, the mean temperature during silo filling was significantly related to certain preservation variables. Average ambient temperature across all silo fillings was 20.0°C and ranged from 14.4 to 28.5°C (SD = 3.4); 70% of silo fillings occurred at average ambient temperatures >18.3°C. Ambient temperature during filling was significantly related to rate of DM loss, change in NSC concentration during storage, final silage pH, and ammonia N concentration. Higher temperatures were correlated with higher rates of DM loss ($r = .42$; $P = .03$); the empirical equation was

$$\text{loss rate} = -10.77 + .702(T)$$

where loss rate = percentage per month, and T = average ambient temperature (degrees Celsius) during filling. Thus, each increase in ambient temperature of 1.5°C during filling was associated with an increased DM loss of 1%/mo. Epiphytic lactic acid bacteria, rate of aerobic activity, and initial temperature of ensiled material depend on ambient temperature during or before filling (17). These factors influence rate of DM loss in the silo (16).

ANOVA

An ANOVA was performed to determine differences between selected preservation variables with silo fillings grouped by level of management. Only significant results are reported.

Filling Variables. When silo fillings were grouped by filling rate in tonnes of DM per day, differences in aerobic instability were significant ($P = .012$). With filling rates in the lowest 25th percentile (<8.3 tonne/d of DM), rate of temperature rise of exposed silage was faster by about 7°C/d. Slower filling may have been associated with increased fungal populations established during the aerobic phase of filling and ensiling (11). A shorter aerobic phase because of faster silo loading may have improved aerobic stability during feedout.

When silo fillings were grouped by filling method, changes in ADF and NSC were significantly different ($P = .009$ and $P = .003$, respectively). The progressive wedge method resulted in increases in ADF that were about 3 percentage points smaller than those for other methods. Mean increases in NSC as a percentage of carbohydrate were about 8 percentage points larger for the progressive wedge method. Apparently, preservation of digestible carbohydrates was improved with progressive wedge filling, which reduced exposed surface area, compared with the full-length method, but permitted easier packing than the full-height method. More effective burial of previously harvested forage also may have limited aerobic respiration during filling.

When silo fillings were grouped by particle size score, differences in change in ADF were significant ($P = .013$). The ADF increased by an average of 5.8 percentage points in silo fillings for which particle size scores were in the uppermost 25%, which corresponds to scores >2.01. Losses of fermentable carbohydrate may have been higher in more coarsely chopped material.

When silo fillings were grouped by packing per mass, aerobic instability was faster by about 5°C/d for the lowest 25% of packing intensity, corresponding to packing <.64 h per tonne, although the differences were not significant (P = .157).

Feedout Variables. When silo fillings were grouped by face condition score, differences in silage ADIN were significant (P = .016). For silos in the lowest 25th percentile, corresponding to face condition ratings <1.45, mean ADIN was nearly 10 percentage points higher. This result is consistent with the significant relationship between these variables and suggests that heat damage of silage was reduced in silos in which face disturbance and oxygen penetration were limited.

Correlations between linear feedout rate and preservation variables produced no significant relationships (Tables 8 and 9). Similarly, when silo fillings were grouped by feedout rate, the preservation variables did not differ significantly. The only comparison approaching significance was the extent of DM loss during storage (P = .185), which averaged nearly 10 percentage points higher (15.9 vs. 6.0%) when feedout rate was in the lowest 25%, corresponding to rates <11.6 cm/d.

DISCUSSION

The DM losses in this study ranged from near 0 to 43% and averaged about 8%. McDonald et al. (11) summarized typical losses in primarily European conditions as 3 to 25%. Buckmaster et al. (2) reported losses cited in the literature between 5 and 14% for all silo types and from 6 to 10% in small bunker silos. Holter (10) measured losses of 10 to 29%, and the Midwest Plan Service (14) cites an average loss of 25% in bunker silos. Overall, losses reported in these studies (2, 10, 14) are similar to or higher than values in the present study. The buried bag technique, which measures losses only at localized positions in the silo, may not have given an accurate overall value. Because bags were not placed closer than 1 m to surfaces, where losses are highest, losses in this study may have been underestimated.

Lower rates of DM loss in the buried bags were associated with lower forage DM. Lower DM content is associated with a more extensive fermentation and greater concentrations of acids that tend to inhibit aerobic losses (11).

Bolsen et al. (1) determined that DM losses in the top 1 m for alfalfa stored in bunker silos were 8% with a plastic cover and 48% without covering. Although all silos in this study were covered with plastic, the significance of the relationship between tire density and surface temperatures and ADIN agrees with the results of Bolsen et al. (1) pertaining to the importance of sealing the top surface.

Filling period in this study ranged from 3 to 32 d, which is somewhat larger than the range of 2 to 10 d reported by Haigh (8) for bunker silos in Wales. Muck (16) identified filling rate as affecting establishment of anaerobic conditions, growth of lactic acid bacteria, substrate availability, DM losses, and ADIN. Woolford (25) noted that >50% of water-soluble carbohydrates can be lost within 24 h of filling if the silo is slowly or inadequately sealed. McGechan (12) cited losses of 1 to 3% in the preseal phase. In the present study, filling period was related strongly to ADIN and change in ADF (Table 7).

Better packing and more rapid sealing are thought to improve aerobic stability of silage at feedout (11, 16, 25). In the present study, aerobic stability increased with packing intensity but was unrelated to duration of the filling period.

Silage DM densities in this study ranged from 100 to 380 kg/m^3 ($\overline{X}$ = 237). Rotz et al. (21) used a DM density of 189 kg/m^3 for bunker silos. Zhao and Jofriet (26) reported wet densities of 560 to 850 kg/m^3, which correspond to DM densities of 200 to 300 kg/m^3 with a DM content of 35%. Darby and Jofriet (3) measured DM densities of grass silage from 175 to 335 kg/m^3. The average density in the present study is within these ranges.

Lower DM content was associated with significantly lower silage temperatures. According to McDonald et al. (11), lower temperatures with lower DM can result from reduced aerobic activity and greater heat capacity of the silage. However, higher packing intensities in this study were associated with higher silage temperatures at 20 cm below the top surface. Given that density and packing were positively correlated, oxygen infiltration and, hence, silage temperature could be expected to be reduced with greater packing. Computer simulations of Pitt and Muck (20) suggested that higher silage density restricts the zone of heating near silage surfaces to a smaller region but intensifies heating within this region. The results of the present study agree, at least qualitatively, with that prediction. Reduced aerobic instability at the exposed face was correlated with greater packing. This result is consistent with lower populations of aerobic organisms that are likely to result with higher density (20).

Oelberg et al. (19) reported silage temperatures in bunker silos that were lower near the bottom of the working face than at the top of the working face. Measurements in the present study followed that trend. Average temperature differences between silage and ambient air across all silo fillings were 12.9°C at the top stratum (13 cm below the top surface), 12.1°C at the middle stratum, and 8.5°C at the bottom stratum (13 cm above the base).

Larger particle sizes were significantly correlated with lower silage temperatures and greater changes in ADF during ensiling. Higher temperature with finer particle size agrees with the suggestion of McGechan (12) that gas movement is easier through smaller particles.

The concentration of SP in this study ranged from 15 to 67% ($\overline{X} = 52$). Muck and Dickerson (18) found that SP increased with temperature between 15 and 35°C in small laboratory silos. In the current study, none of the N fractions was correlated with silage temperatures or with DM content ($P > .208$). However, SP was negatively correlated with pH ($r = -.587$; $P < .001$), which in turn was negatively correlated with DM content when silo number 8 was removed from the regression. Because SP and ADIN were negatively correlated, factors affecting ADIN also affected SP and may have masked a relationship between SP and DM.

Concentrations of ADIN in this study ranged from 3.6 to 44.6% of total N ($\overline{X} = 10$). Oelberg et al. (19) reported ADIN of 24 to 42% of total N in 44% DM forage stored in bunkers 1.5 m deep. The higher values of Oelberg et al. (19) may have resulted from small silo dimensions and more uniform browning. Goering et al. (6) associated Maillard reactions in silage with ADIN >14% of total N. In a survey of silages from tower silos, Goering and Adams (5) found that ADIN exceeded 14% in 30% of samples. In the present study, 7 silo fillings, or 23% of the silages, had ADIN >14%. Thus, the incidence of heat damage in this study apparently was similar to that reported by Goering and Adams (5). Given the relationship between ADIN and surface sealing, Maillard reactions might be even more prevalent in silos without covers (13).

Garcia et al. (4) observed an increase in ADIN with silage temperature between 38 and 60°C. In the current study, ADIN was not correlated with silage temperature at the top surface or at the working face. However, silage temperatures were 34°C on average, and 79% of silo fillings had temperatures <41°C. Thus, the majority of temperatures were below the range of Garcia et al. (4), which may explain the lack of a relationship. Van Soest (24) reported that temperatures >30°C can result in Maillard products. The occurrence of browning in this study supports that observation.

CONCLUSIONS

Bunker silo management practices on the commercial farms in this study exhibited greatest variation in filling rate, filling period, packing, and density of tires used to weight down the top cover. Management variables having the strongest correlation with silage preservation were silo filling rate, tire density, packing intensity, particle size, DM content, and face condition rating. Preservation variables that were correlated significantly with management included increase in ADF and NSC during storage, silage ADIN, SP, ammonia N, pH, temperature at the top surface, and aerobic instability. Packing intensities >.64 h·tonne per tonne were associated with higher silage densities, lower losses, and greater aerobic stability. Average silo filling period was 9.3 d with a 27% delay. Filling periods ≥10 d were associated with higher ADIN. Silos filled by formation of angled wedges had increases in ADF that were 3 percentage points lower than those filled by formation of horizontal or vertical layers. Face condition ratings were negatively correlated with ADIN. Silos with linear feedout rates ≥11.6 cm/d averaged 10 percentage points lower in extent of DM losses.

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