EVALUATION OF METHODS TO IMPROVE STORAGE CHARACTERISTICS OF LARGE SQUARE BALES IN A HUMID CLIMATE

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ABSTRACT. *Three methods to improve the storage characteristics of large square bales were investigated. These methods included: treatment with propionic acid, treatment with a bacterial inoculant, and formation of an 8 or 12-cm diameter vent hole through the bale center. Bale moisture ranged from 14 to 28% (w.b.). Ventilated bales did not produce evidence of less heating in storage compared to untreated bales (control). Also, ventilated bales generally produced a similar change in the ratio of bound protein, indicating similar heat damage to the control. When bale moisture was greater than 25% (w.b.), treatment with 0.8% propionic acid produced less bale heating and less heat damage to proteins compared to the control. Over all trials, no preservation technique significantly reduced DM loss compared to the control. However, in three of four trials, bales with the 12-cm vent hole had numerically lower DM loss compared to the control. In three of four trials, bales treated with propionic acid had numerically higher DM loss compared to the control. Treatment with inoculant produced numerically lower DM loss than the control in two trials. None of the preservation techniques significantly reduced fiber concentration compared to the control. In three of four trials, bales treated with propionic acid maintained higher moisture during storage compared to other treatments. This may have lead to a longer period of biological activity that offset the suppressed rate of microorganism activity from the acid treatment. Increased bale DM loss and reduced quality were related to initial bale moisture. The key to maintaining bale quality and keeping DM loss below 4% was baling at moisture contents below 16% (w.b.).*

Keywords. *Forage, Storage, Drying, Large square bales, Propionic acid.*

North American sales of large square balers have increased steadily throughout most of the 1990s. Large square bales have three basic cross-sections: 80 × 80 cm, 80 × 120 cm or 120 × 120 cm. The larger cross-section balers are used almost exclusively in the arid western U.S. for commercial hay production. The 80 × 80 cm balers are appropriate for hay and forage producers east of the Mississippi River because bale mass and size are more manageable for smaller farms limited by handling capability and livestock facility layout. Large square balers have greater productivity and produce lower field losses than either large round or small square balers (Shinners et al., 1996). Large square bales formed in arid regions typically have low moisture, so the hay tends to be stable during storage. As this bale size has become more prevalent in humid regions, storage problems have been noted (Shinners et al., 1996).

Large square balers typically have a precompression chamber and hydraulically loaded panels on three sides of the bale chamber, both of which help to produce a high-density bale. Shinners et al. (1996) determined that large square bale (80 × 80 cm) density was 54% greater than small square bale density. Nelson (1966) and Buckmaster et al. (1989) both found a strong correlation between bale density and heating. Heat generation occurs in hay bales when organic matter, primarily carbohydrates, serve as an energy source for microbial respiration. The chemical reaction of respiration involves the conversion of carbohydrates and oxygen into carbon dioxide, water, and heat. This conversion of carbohydrates results in dry matter (DM) loss and increased bale temperature. The rise in bale temperature can have a detrimental effect on hay quality by binding proteins to fiber and rendering these proteins unavailable to the animal (Yu, 1977).

Shinners et al. (1996) found that 80 × 80 cm square bales stored slightly over four months exhibited greater heating, greater DM loss, and lower quality (ADF, NDF and CP) than small square bales at similar moistures (16 to 21% w.b.). This difference in storage characteristics was thought to be due to two primary factors. First, for a given volume of hay, a greater amount of DM and carbohydrates are available in the high-density large square bale. Therefore, greater microbial activity and heating can be expected per unit volume. Nelson (1966) found that the heat generated per unit mass of alfalfa hay during storage increased with greater bale density. Secondly, the greater volume of the large bale may have an adverse effect on heat transfer and moisture diffusion properties. It is possible that heat and water vapor from the bales moves to the exterior and is lost from the stack through air movement in the spaces between bales. With the large bales, this potential transfer is less due to their greater

Article was submitted for publication in October 1999; reviewed and approved for publication by the Power & Machinery Division of ASAE in March 2000. Presented as ASAE Paper No. 99-102.

Research sponsored by the College of Agriculture and Life Sciences at the University of Wisconsin-Madison, Hay and Forage Industries, Case Corporation , John Deere Ottumwa Works, Harvest Tec, and Minnesota Valley Alfalfa Producers. Trade names are used solely to provide specific information and do not imply endorsement of the product by the University of Wisconsin-Madison.

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volume and correspondingly less space for air movement for a given stack volume.

Hay producers may use chemical preservatives to reduce storage losses. The most common is propionic acid, which is intended to reduce microbial growth and subsequent heating. Typical application rates are 0.5 to 2% of hay mass. Rotz et al. (1991) found propionic-acid-treated hay at high moisture (22 to 26% w.b.) had greater DM and nutrient loss after six months in storage compared to a typical low moisture system (11 to 15% w.b.). Rotz et al. (1992) also did not find economic justification for treating high moisture hay (20 to 28% w.b.) with propionic acid compared to the conventional low moisture system. There is a lack of research concerning bale storage characteristics of large square bales in the range of 15 to 22% moisture (w.b.) treated with propionic acid. It is very common for producers in humid regions to apply 0.5 to 1% propionic acid by mass when baling with a large square baler (Roberts, 1998).

There is recent interest in the use of a hole in the center of large square bales to create an egress for bale moisture and heat. This idea is not new; Rotz et al. (1993) reported that bale manufacturers experimented with such a concept on small square balers nearly 50 years ago. In the past, devices designed to form a center vent hole typically consisted of a spear fixed to the small square baler plunger. As each bale slice was formed, the conical spear created a hole in the slice. The vent hole diameter typically ranged from 4 to 5 cm. Rotz et al. (1993) found that small square bales formed with such a vent hole did not reduce heating during storage nor improve bale quality out of storage. However, DM loss and level of bound protein were slightly less in the ventilated bales. Rotz et al. noted that hay around the formed hole had a greater density than at the center of control bales.

Another approach to forming vent holes in the center of the bale involves placing a cutting or boring device on the plunger face (Stromer and Winston, 1994). A cut hole may have advantages over a hole created by a spear because material around the hole would have the same density as the rest of the bale as opposed to the compressed nature of hay around a hole formed by the spear. The boring device described by Stromer and Winston (1994) had a hollow boring tube with a cutting tip at the leading edge. An auger was placed inside the tube to pull the cut plug from the tube to prevent blockage. A hydraulic motor using tractor hydraulics powered both the tube and the auger.

The specific objectives of this research were to: (1) investigate methods to improve the storage characteristics (heat damage, DM loss, fiber concentration) of large square bales in a humid climate, specifically through treatment with propionic acid, bacterial inoculants or formation of vent holes in the bale center; (2) determine the effect of hole diameter on the storage characteristics of ventilated large square bales; and (3) determine if any practical limitations exist concerning the handling and storage of large square bales with a vent hole.

Description of Bale Boring Device

Since a goal of this project was to bore holes of different sizes in the bales, creating the vent hole on the baler was not a viable option. Rather, a device was designed and fabricated that allowed boring outside the baler. Some design objectives for this apparatus were to: (1) bore holes of 8 and 12 cm diameter; (2) bore without creating excess heat that would melt forage waxes and seal the edge of the hole; and (3) create a hole in one pass through the bale. The design chosen to bore the bale vent holes was a tube with a cutting surface attached to its leading edge. The tube was forced into the bale and the cut material formed a plug inside the tube. A driving device for powering the tube was placed on the three-point hitch of a tractor. The tube was forced through the bale by slowly backing the tractor toward the bale, a method that provided more than adequate pushing force. An axial-piston hydraulic motor powered by tractor hydraulics, and driven through a 5:1 reduction planetary gear set drove the cutting tube at about 50 rpm. A sprocket was attached to the gear drive output shaft and a similar size sprocket welded to the end of each boring tube. The tube was attached to the drive through a double chain coupler. This design allowed tubes to be changed quickly and allowed power transmission to the tube despite inevitable misalignment between the tube and the drive system. The cutting rate through the bale was about 1.5 m/min. To resist the tube pushing force, large oak blocks were placed between the bale and a concrete wall at the far end of the bale. Generally, the tube center exited within about 5 cm of the bale center (fig. 1).

The tubes were either 7.6 or 11.7 cm diameter with a 7.6 or 11.7 cm cutting ring attached to the tube. Hereafter, these two sizes will be referred to as 8 and 12 cm. The cutting surface was a conventional metal hole saw (2 teeth/cm) with the back removed. This cutting ring was welded to the tube with the internal interface between the cutting ring and the tube polished smooth. This design worked adequately to produce a hole completely through the bale without excessive pushing force. The tube was warm when it was removed from the bale, but could easily be handled with bare hands without discomfort. Under most conditions, the 8 cm tube could be forced through the bale in one pass, while the 12 cm tube required the tube to be pulled about half-way through the bale to remove the plug.

When cutting either 8 or 12-cm diameter holes in the bale center, it was observed that the bale became compressed as the tube was forced through and the bale twines became slightly slack. When the boring tube was removed, the bale re-expanded to its original size. However, when subsequently moved, the bale was

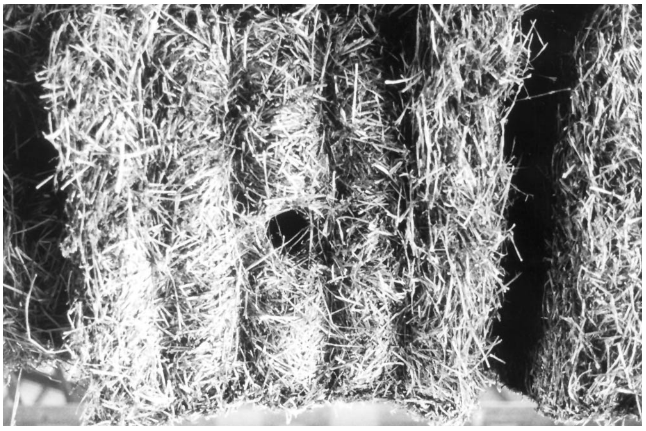

Figure 1–Exit location of hole started in bale center.

observed to sag slightly more than those bales that had not been bored. If the bored bale was moved too roughly with the skid-steer loader, then this sagging would make it difficult to force a slightly undersized pipe through the recently created hole and light could not be observed through the 8 cm hole. This tendency for bale sagging to disrupt the integrity of the hole was overcome by always transporting the bale with a pipe placed through the vent hole. Bale density on a dry basis as determined as bales were placed into storage was not different among treatments (data not presented).

PROCEDURES

TESTS CONDUCTED IN 1997

Tests were conducted at the University of Wisconsin Arlington Agricultural Research Station using first and second cuttings of alfalfa at about one-fourth to one-half bloom stage of development. Forage was cut using a 3-m sickle cutterbar mower-conditioner and placed into a swath about 2.0 m wide. Two swaths were raked into a single windrow with a parallel-bar rake the morning of the day of baling. Baling started about 3:00 P.M. and was completed by 5:30 P.M. for both cuttings. First cutting alfalfa was cut on 7 June and baled on 11 June 1997. Drying conditions were considered good (table 1); however, a 10 mm shower occurred soon after cutting on 7 June. Second cutting alfalfa was cut on 8 July and baled on 11 July 1997 and drying conditions were considered good (table 1).

Hay was baled with a Case IH model 8575 baler with an 80 × 87.5 cm bale chamber cross-section and 41 strokes/min plunger frequency. The baler was operated at about 9 km/h and with a plunger load of about three-fourths of maximum. Bales were tagged with an identification number as they exited the baler. A total of 12 usable bales were formed for each of four treatments. Bales intended as controls or to be bored with vent holes were baled first, followed by bales with propionic acid. Propionic acid was applied with a Harvest Tec model 491 applicator and model 453 flow meter calibrated to provide 0.5% by hay mass through five spray nozzles located above the baler pick-up. When propionic acid was applied, the applicator was switched on and the first bale out of the baler was discarded in order to insure that equilibrium conditions were obtained. Likewise, when the applicator was turned off, the first bale without propionic acid was also discarded. All bales were transported to the storage area and stored under cover the evening of baling. Boring of the vent holes in randomly selected bales began immediately the morning after bale formation. Total time to select, set up, and bore a bale was approximately 20 min.

Table 1. Average daytime (8:00 A.M. to 6:00 P.M.) drying conditions during hay drying period

Date	Temp. (°C)	Solar Radiation (W/m^2)	Relative Humidity (%)	Total Precipitation During Drying Period (mm)
7 to 11 June 1997	21	520	66	10
8 to 11 July 1997	22	641	65	0
11 to 15 July 1998	26	656	64	0
27 to 31 July 1998	24	607	61	1

Therefore, a complete set of bored bales was accomplished within 24 h of baling. Some of the bales with vent holes did show some evidence of heating before the vent hole was formed. All bales were placed into storage the day following boring (i.e., within 48 h of formation).

As the bales were placed into storage, they were weighed on a platform scale to the nearest 0.5 kg. When placed into storage, all bales were sampled for moisture and nutrient content determination with a 50-mm-diameter boring device to a depth of about 50 cm. The boring location was in the center of the upper left quadrant of the bale cross-section, about 30 cm from the center of the bale. All samples were oven dried at 65°C for 72 h in accordance with ASAE Standard S358.2 (ASAE, 1999). These samples were then analyzed using near-infrared spectroscopy (NIRS) by the University of Wisconsin Soil and Plant Analysis Laboratory for crude protein (CP), acid-detergent fiber (ADF), neutral-detergent fiber (NDF), and acid-detergent insoluble protein (ADIP). Twelve bales from each of the four treatments were stacked two across by two deep by three high. Each stack of 12 bales was surrounded on four sides by small square alfalfa bales that had been in storage for about one year. The barrier wall was one bale wide (350 mm). The large square bale stacks were not covered. A vertical channel was formed between bales with vent holes by leaving a gap of about 20 cm between the end of each bale and/or the adjacent buffer wall. All bales were stored in an open-front hay storage structure.

Probes containing four copper-constantan thermocouples were placed into four bales of each treatment. The bales with thermocouples were the bottom four of the left-hand set. Thermocouples on these probes were on 25 cm centers with the innermost thermocouple approximately 85 cm from the end of the bale. These probes were placed in the upper right quadrant of the bale about 30 cm from the bale center. In second cutting ventilated bales, additional thermocouple probes were inserted 5, 13, and 20 cm from the edge of the vent hole, to a depth of about 60 cm, in two random bales per treatment. All thermocouples were connected to a stepping switch that allowed a Campbell Scientific model 21X datalogger to record the data from all thermocouples. The datalogger was programmed to read and download temperatures to a storage module on a 12 h interval (noon and midnight). The temperature data was downloaded from the storage module to a microcomputer for further processing.

First cutting bales were placed in storage with thermocouples inserted on 13 June 1997. The thermocouples were removed after 27 days. Second cutting bales were placed in storage with thermocouples inserted on 14 July 1997. The thermocouples were removed after 47 days. Both first and second cutting bales were removed from storage on 1 November 1997. At that time the final bale mass was determined and all bales were again bored for moisture and nutrient determination using the same procedure described above except that boring took place in the upper right quadrant. Also at the time the bales were removed from storage, separate bore samples (25 mm diameter, 45 cm depth) were taken 5, 13, 20, and 30 cm from the edge of the vent holes from five random bales from each cutting. Moisture and nutrient determination were made on all samples using the same procedure described above.

For both cuttings, four treatments, control, treated with 0.5% propionic acid, and 8 or 12 cm vent holes bored in the center of the bale, were considered. Average and maximum bale storage temperature, bale DM loss, and nutrient data for each cutting and treatment were analyzed using an analysis of variance. Bale temperature at any given sampling period was defined as the average temperature from the four thermocouples located in each bale. A least squares difference (LSD) was then calculated to determine statistical differences (P = 0.05).

Tests Conducted in 1998

Tests were conducted at the University of Wisconsin Arlington Agricultural Research Station using second cutting of alfalfa at about one-third to three-fourths bloom stage of development. Forage was cut using a 4-m disk cutterbar mower-conditioner and placed into a swath about 2.5 m wide. Two swaths were raked into a single windrow with a rotary rake the morning of the day of baling. Forage for a first trial was cut on 11 July and baled on 14 and 15 July 1998. Forage for a second trial was cut on 27 July and baled on 29 and 30 July 1998. Weather during both drying periods was considered very good (table 1).

Hay was baled with a John Deere model 100 baler with an 80 × 80 cm bale chamber cross-section and 50 strokes/min plunger frequency. The baler was operated at about 9 to 11 km/h and plunger load was set at about three-fourths of maximum. During each day baling was conducted, every fourth windrow was baled until at total of six usable bales per day per treatment were formed.

In 1998, four treatments, control, treated with propionic acid, treated with bacterial inoculant and treated with a 12-cm vent hole, were used. Propionic acid was applied with a Harvest Tec model 491 applicator and model 453 flow meter calibrated to provide 0.3 to 0.8% by weight through five spray nozzles located above the baler pick-up. A propionic application rate of 0.3, 0.5 or 0.8% was used when bale moisture was below 19, from 19 to 23 and above 23% (w.b.), respectively, based on manufacturers recommendations. Initial moisture content for determination of propionic acid rate was estimated through the use of a Delmhorst model F-2000 hand-held conductance moisture sensor. Pioneer 1155 inoculant was premixed at the rate of 20 g/19 L tap water and the mixture was applied at about 4.2 L/Mg dry hay. Based on label analysis, this application rate resulted in an inoculation of 99,000 colony forming units (CFU) of *Bacillus* inoculum/g dry hay. Inoculant was applied through the same spray system used for the propionic acid treatment described above. To prevent harmful effects on the bacteria from propionic acid, the inoculant treatment was always applied before propionic treatment and before either treatment was placed in the system tank, the system was first flushed with about 400 L of tap water. When either propionic acid or inoculant was to be applied, the first and last bale of each treatment was discarded to insure that equilibrium conditions were obtained.

Bales were placed into storage, weighed and sampled for moisture and nutrient determination in the same fashion as described in the previous 1997 tests. Moisture content and quality constituents were determined as described previously except that the University of Minnesota NIRS Forage Quality Laboratory conducted NIRS analysis. Instrumentation problems prevented use of the same bale temperature monitoring system as used in 1997. In 1998, a single copper-constantan thermocouple was placed into six random bales of each treatment formed on 29 or 30 July 1998. Thermocouples were placed about 60 cm deep into the center of the upper left quadrant of the selected bales. Temperatures were determined using an Omega model NR-99 thermocouple measurement device every other day from 31 July to 4 September 1998. Statistical analysis was similar to that described previously.

Results

Bale Storage Temperature

In first cutting bales, thermocouples were placed in the upper right quadrant of the bale cross-section approximately 30 cm from the bale center. At this location, bale-heating characteristics did not suggest that the ventilated bales produced less heating than the control (figs. 2 and 3). Temperature history of the bales with the 8 cm vent hole were similar to the control and the bales with the 12 cm vent hole had a greater number of days above 35°C than the control treatment (table 2). The level of heat damage to proteins is proportional to the number of degree-days hay is above 35°C (Rotz and Muck, 1994). Bales treated with propionic acid also had evidence of greater bale heating than the control bales (fig. 2, table 2). However, independent of treatment, there was a correlation between initial bale moisture and heating (table 2). The relatively low initial moisture of the control bales is likely the reason this treatment produced the lowest level of heating. In second cutting bales, moistures were relatively low, so little adverse heating took place in any of the treatments. The average temperature 30 cm from the bale center for all treatments was under 26°C and none of the bales exhibited temperatures above 35°C (table 2).

In random second cutting bales, thermocouples were also placed about 5, 13, 20 and 30 cm radially from the edge of the vent hole. For bales with the 8 cm vent hole, there was no apparent difference in hay temperature at these four locations (data not presented). For bales with the 12-cm vent hole, hay temperature increased from the 5 to

Table 2. Bale moisture and heating characteristics for first and second cutting alfalfa hay, 1997 and 1998

Treatment	Control	Propi-onic Acid	8 cm Vent Hole	Inocu-lant	12 cm Vent Hole	LSD* (P = 0.05)
			Baled 12 June 1997			
Initial MC (% w.b.)	16.3_a	18.8_{ab}	17.7_{ab}		19.6_b	2.5
Ave. bale temp. (°C)	29.0	34.6	31.6		36.1	
HDD > 35°C (°C-day)	0	16	2		20	
			Baled 14 July 1997			
Initial MC (% w.b.)	14.2	15.0	14.4		14.3	1.4
Ave. bale temp. (°C)	23.6	24.1	25.6		24.4	
HDD > 35°C (°C-day)	0	0	0		0	
			Baled 29 and 30 July 1998			
Initial MC (% w.b.)	27.6	26.6		25.3	27.5	2.3
Ave. bale temp. (°C)	47	41		46	44	
HDD > 35°C (°C-day)	35	33		35	34	

* Alphabetic subscripts in rows denote statistical difference @ P = 5%.

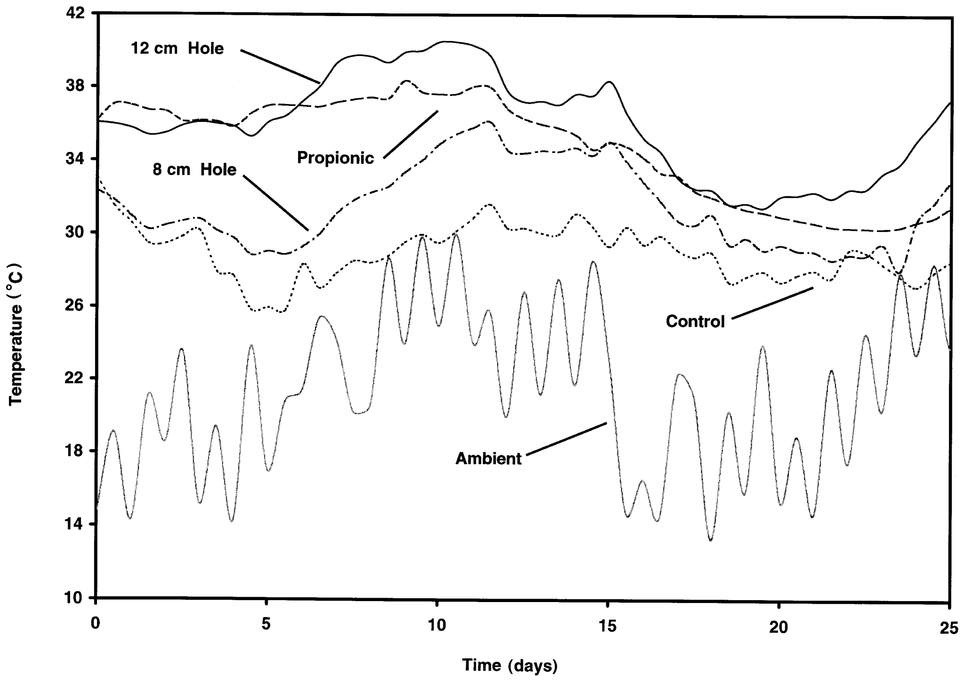

Figure 2–Bale temperature history for first cutting, 1997.

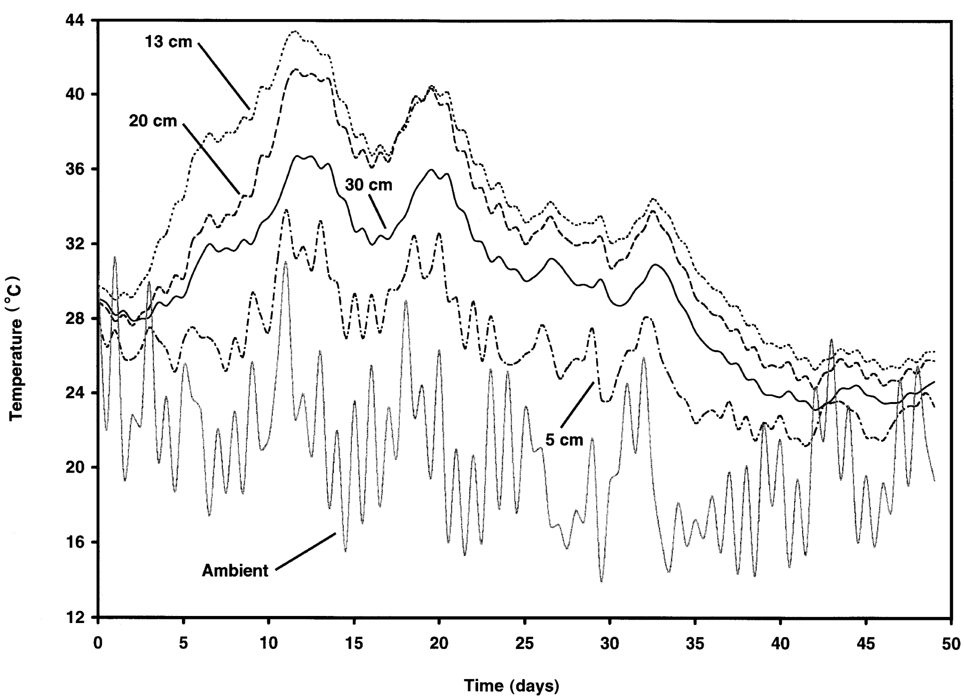

Figure 3–Bale temperature history for second cutting (1997) at varying radial distances from a 12-cm vent hole.

13-cm radial position, and then dropped progressively from the 20 and 30 cm positions, respectively (fig. 3). The temperature at the 5-cm position mirrors the diurnal fluctuation of ambient temperature, albeit with less amplitude (fig. 3). Additionally, these diurnal fluctuations were apparent at each of the remaining three radial positions, with less amplitude at each position further from the vent hole. The high temperature at the 13 cm location may have been due to localized high moisture. These results suggest that the vent hole had little effect on heating even as close as 13 cm from the edge of the hole. On the other hand, the obvious diurnal temperature fluctuations indicate that significant air exchange did take place within the bale due to the vent hole. The fact that these diurnal fluctuations are readily apparent for the bales with the 12-cm vent hole and not with the 8 cm hole might suggest that the latter hole size was insufficient to produce air exchange in the bale.

Only random bales were used to measure bale temperature during 1998 and these bales had considerably

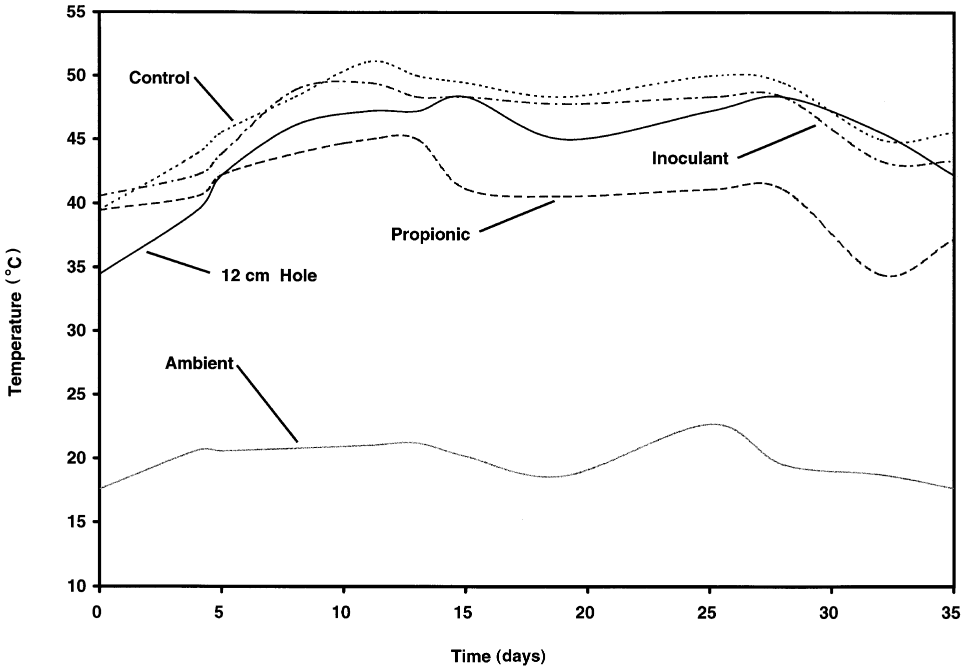

Figure 4–Bale temperature history for second cutting, baled 29th and 30th July 1998.

higher moisture than those used in 1997, thus average bale temperatures were higher in 1998 (table 2). The application of 0.8% propionic acid reduced bale heating during storage (fig. 4). Temperature profiles were similar for the control, inoculant and vent hole bales (fig. 4). The application of propionic acid may have reduced bale heating more in 1998 than 1997 because of a slightly higher application rate (0.8 vs 0.5%) and higher bale moistures which created overall higher levels of heating in all treatments.

Dry Matter Loss

Considerable variation existed in storage DM loss within treatments and thus there were no significant differences in DM retention between treatments (table 3). In first cutting bales, there was a trend for the bales with the 12-cm vent hole to have lower DM loss than the other treatments. The fact that this trend was not evident for the bales with 8-cm vent holes suggests that the larger vent hole was more effective in preserving bale DM in storage. This also may confirm the results suggested in figure 3 where the larger vent hole appeared to produce greater air exchange in the bale. In second cutting bales, control bales had the lowest DM loss numerically but also the lowest initial moisture, although there were no significant differences across treatments. All second cutting bales were relatively dry and the level of DM loss was correspondingly low.

Table 3. Dry matter loss in storage for first and second cutting alfalfa hay, 1997 and 1998

Treatment	Control	Propionic Acid	8 cm Vent Hole	Inoculant	12 cm Vent Hole	LSD* (P = 0.05)
Baled 12 June 1997						
Initial MC (% w.b.)	16.3_a	18.8_{ab}	17.7_{ab}		19.6_b	2.5
Final MC (% w.b.)	16.6_a	18.0_b	16.6_a		16.7_a	1.1
DM loss (% of total)	6.0	5.6	6.1		4.0	2.7
Baled 14 July 1997						
Initial MC (% w.b.)	14.2	15.0	14.4		14.3	1.4
Final MC (% w.b.)	15.5_a	16.9_b	15.6_a		15.4_a	1.0
DM loss (% of total)	2.5	3.7	3.2		3.7	1.2
Baled 14 and 15 July 1998						
Initial MC (% w.b.)	15.8	15.9		15.6	15.8	1.4
Final MC (% w.b.)	16.5	16.7		16.2	16.5	0.6
DM loss (% of total)	3.8	3.9		3.4	3.0	1.0
Baled 29 and 30 July 1998						
Initial MC (% w.b.)	27.6	26.6		25.3	27.5	2.3
Final MC (% w.b.)	17.7_b	23.3_c		16.6_a	16.8_{ab}	0.9
DM loss (% of total)	12.2_{ab}	13.3_b		10.9_a	11.1_a	1.6

* Alphabetic subscripts in rows denote statistical difference @ P = 5%.

In 1998, bale moisture significantly affected the level of DM loss. Greater bale moisture in the second trial resulted in greater DM loss than the lower moistures in the first trial (table 3). The ventilated bales formed on 29 and 30 July had significantly or numerically lower DM loss than the propionic treatment (table 3). Bales treated with inoculant had a trend for less DM loss compared to the control bales, although this difference was not significant. Bales treated with propionic acid had the numerically highest DM loss. These bales also retained moisture during the storage period compared to other treatments (see discussion below).

Bale Nutrient Quality Changes

Crude protein (CP) concentration was generally not affected by any of the treatments (tables 4 and 5). The main energy source for microbial growth is carbohydrates and CP is usually consumed at a lower rate. The loss of CP is greater over 6 to 9 months of storage than with a shorter storage period because as storage proceeds, the rate of carbohydrate loss declines but CP loss continues (Rotz and Muck, 1994). In this study, bales were in storage for a maximum of 4 months, which could account for the low

Table 4. Bale quality constituents in storage for first cutting alfalfa hay baled 12 June 1997

Treatment	Control	Propionic Acid	8 cm Vent Hole	12 cm Vent Hole	LSD* (P = 0.05)
Initial MC (% w.b.)	16.3_a	18.8_{ab}	17.7_{ab}	19.6_b	2.5
Final MC (% w.b.)	16.6_a	18.0_b	16.6_a	16.7_a	1.1
Initial CP (% DM)	23.3	23.0	22.8	22.9	2.0
Final CP (% DM)	23.4	23.1	23.4	23.0	1.1
Ratio of final to initial CP	1.01	1.00	1.03	1.01	0.05
Initial ADF (% DM)	31.9_b	32.3_{ab}	32.2_{ab}	33.2_a	1.0
Final ADF (% DM)	34.3	34.4	33.3	33.5	1.5
Ratio of final to initial ADF	1.07_b	1.07_b	1.03_{ab}	1.01_a	0.05
Initial NDF (% DM)	39.4	40.1	40.2	40.8	1.6
Final NDF (% DM)	42.7	42.4	41.2	41.9	2.1
Ratio of final to initial NDF	1.09_a	1.06_{ab}	1.03_b	1.03_b	0.05
Initial ADIP (% DM)	0.74	0.75	0.75	0.75	0.07
Final ADIP (% DM)	0.84_a	0.83_{ab}	0.76_b	0.78_{ab}	0.07
Ratio of final to initial ADIP	1.15_a	1.11_{ab}	1.01_b	1.04_{ab}	0.13

* Alphabetic subscripts in rows denote statistical difference @ P = 5%.

Table 5. Bale quality constituents in storage for second cutting alfalfa hay baled 14 July 1997

Treatment	Control	Propionic Acid	8 cm Vent Hole	12 cm Vent Hole	LSD* (P = 0.05)
Initial MC (% w.b.)	14.2	15.0	14.4	14.3	1.4
Final MC (% w.b.)	15.5_a	16.9_b	15.6_a	15.4_a	1.0
Initial CP (% DM)	16.8	17.1	17.3	17.6	0.7
Final CP (% DM)	18.2	17.8	18.2	18.2	0.8
Ratio of final to initial CP	1.09	1.04	1.06	1.04	0.66
Initial ADF (% DM)	36.7	36.2	35.6	35.5	2.3
Final ADF (% DM)	35.3	34.8	35.6	34.7	2.0
Ratio of final to initial ADF	0.96	0.97	1.00	0.98	0.07
Initial NDF (% DM)	46.5	45.9	45.5	45.4	2.6
Final NDF (% DM)	44.9	44.4	44.9	43.9	2.5
Ratio of final to initial NDF	0.97	0.97	0.99	0.97	0.07
Initial ADIP (% DM)	0.71	0.72	0.71	0.71	0.03
Final ADIP (% DM)	0.70	0.67	0.71	0.71	0.05
Ratio of final to initial ADIP	0.99	0.94	1.00	1.00	0.08

* Alphabetic subscripts in rows denote statistical difference @ P = 5%.

CP loss. Rotz and Abrams (1988) found that CP concentration actually increased for small square bales while Shinners et al. (1996) found that CP concentration decreased for large square bales. In 1997, CP concentration was essentially neutral to slightly positive.

In first cutting bales, both control and propionic treated bales had greater increases in ADF and NDF concentrations than ventilated bales (table 4). Neither NDF or ADF components are lost during storage; DM loss is mainly soluble carbohydrates. Therefore, the increase in fiber concentration as measured by ADF and NDF concentration is due to loss of other carbohydrates. These results would tend to confirm the trends found with DM loss, i.e., that the 12-cm vent hole appeared to reduce bale DM loss compared to the control and propionic acid treatments and this hole size appeared to provide better bale quality than the 8 cm hole. There were no significant differences between treatments with respect to fiber concentration in the second cutting bales, likely because of the low initial bale moisture (table 5). Shinners et al. (1996) found ADF and NDF retention ratios of about 1.07 to 1.09 for bales at about 17% moisture (w.b.). This was about the same range found in this study for the control and propionic acid treatments in the first cutting.

When excessive bale temperature (> 35°C) occurs due to microbial respiration, protein availability is reduced because some protein can become tightly bound to fiber. Bound protein usually measured by acid-detergent insoluble protein (ADIP). In first cutting bales, the control and propionic acid treatments resulted in a significant or numerically higher ratio of final to initial ADIP compared to the ventilated bales (table 4). This result indicates that excess heating took place in these treatments, which contradicts the temperature results (table 2, fig. 2). Temperature was measured in four bales in the each stack, and it is possible that heating was lower in these bales than on the remaining eight bales in the stack. Since the ADIP values are an average of samples from all 12 bales in each stack, this parameter might be a better indication of the level of heating for each treatment. In second cutting bales, none of the treatments produced a significant difference in the ratio of final to initial ADIP and the ratios were near one, indicating little bale heating (table 5). This result was consistent with the relatively low bale moisture for this cutting (table 2).

There were no significant differences in moisture, CP, ADF, NDF or ADIP at varying radial distances from the edge of the vent hole (tables 6 and 7). Also, the moisture and quality constituents in proximity to the vent hole did

Table 6. Final quality constituents by radial location of first and second cutting alfalfa hay baled at an average of 16% w.b. moisture and bored with 8 diameter cm vent hole

Distance from Edge of Vent Hole	MC (% w.b.)	CP (% DM)	ADF (% DM)	NDF (% DM)	ADIP (% DM)
5 cm	15.7	20.7	34.3	43.1	0.75
13 cm	15.7	20.6	34.6	43.1	0.76
20 cm	15.6	20.4	35.6	44.9	0.77
30 cm	15.9	20.7	34.6	43.4	0.76
LSD* (P = 0.05)	0.5	0.8	1.4	1.9	0.04

* Alphabetic subscripts in rows denote statistical difference @ P = 5%.

Table 7. Final quality constituents by radial location of first and second cutting alfalfa hay baled at an average of 17% w.b. moisture and bored with 12 cm diameter vent hole

Distance from Edge of Vent Hole	MC (% w.b.)	CP (% DM)	ADF (% DM)	NDF (% DM)	ADIP (% DM)
5 cm	15.5	20.9	33.3	41.6	0.73
13 cm	15.7	20.4	34.0	42.9	0.74
20 cm	15.6	20.8	34.0	42.9	0.75
30 cm	16.0	20.3	34.3	43.1	0.73
LSD* (P = 0.05)	0.7	0.8	1.2	1.6	0.04

* Alphabetic subscripts in rows denote statistical difference @ P = 5%.

not vary significantly from those taken at the upper right quadrant of the bale (tables 4 and 5).

For alfalfa baled on 14 and 15 July in 1998, the ratio of final to initial CP was essentially neutral (table 8). The control and inoculant treated bales experienced a slight increase in CP, but this was most likely due to low initial CP content compared to other treatments. For crop baled on 29 and 30 July, CP concentration appeared to increase during storage (table 9). Crop baled on these dates had relatively high moisture and experienced a large DM loss from microbial respiration (table 3). Because the primary energy source for microbial action is carbohydrates and CP is usually consumed at a lower rate, when large DM loss occurs, CP concentration rises.

Table 8. Bale quality constituents in storage for second cutting alfalfa hay baled 14 and 15 July 1998

Treatment	Control	Propi-onic Acid	Inocu-lant	12 cm Vent Hole	LSD* (P = 0.05)
Initial MC (% w.b.)	15.8	15.9	15.6	15.8	1.4
Final MC (% w.b.)	16.5	16.7	16.2	16.5	0.6
Initial CP (% DM)	15.7_a	17.0_b	15.9_a	16.3_{ab}	0.8
Final CP (% DM)	16.6_b	16.7_b	16.3_{ab}	15.9_a	0.6
Ratio of final to initial CP	1.06_c	0.98_a	1.02_b	0.98_a	0.03
Initial ADF (% DM)	38.7_b	36.5_a	38.4_b	37.5_{ab}	1.5
Final ADF (% DM)	37.5_{ab}	36.9_a	38.2_b	38.2_b	0.9
Ratio of final to initial ADF	0.97_a	1.01_b	1.00_{ab}	1.02_b	0.03
Initial NDF (% DM)	46.4_b	43.6_a	45.8_b	45.2_{ab}	1.6
Final NDF (% DM)	46.0_{ab}	45.3_a	46.3_{ab}	46.5_b	1.1
Ratio of final to initial NDF	0.99_a	1.04_b	1.01_{ab}	1.03_b	0.03
Initial ADIP (% DM)	0.75_{ab}	0.72_a	0.74_{ab}	0.76_b	0.03
Final ADIP (% DM)	0.77_c	0.70_a	0.73_b	0.75_{bc}	0.02
Ratio of final to initial ADIP	1.03_b	0.97_a	0.99_{ab}	0.99_{ab}	0.04

* Alphabetic subscripts in rows denote statistical difference @ P = 5%.

Table 9. Bale quality constituents in storage for second cutting alfalfa hay baled 29 and 30 July 1998

Treatment	Control	Propi-onic Acid	Inocu-lant	12 cm Vent Hole	LSD* (P = 0.05)
Initial MC (% w.b.)	27.6	26.6	25.3	27.5	2.3
Final MC (% w.b.)	17.7_b	23.3_c	16.6_a	16.8_{ab}	0.9
Initial CP (% DM)	20.9	21.6	21.5	20.9	0.7
Final CP (% DM)	22.4_{ab}	21.8_a	22.1_{ab}	22.8_b	0.7
Ratio of final to initial CP	1.07_b	1.01_a	1.03_a	1.09_b	0.03
Initial ADF (% DM)	29.1	28.7	28.6	29.6	1.2
Final ADF (% DM)	34.2_b	31.8_a	33.3_{ab}	33.5_{ab}	1.9
Ratio of final to initial ADF	1.18_b	1.11_a	1.17_{ab}	1.13_{ab}	0.06
Initial NDF (% DM)	35.3	34.0	34.2	35.1	1.5
Final NDF (% DM)	43.1_b	40.7_a	41.6_{ab}	42.4_{ab}	1.9
Ratio of final to initial NDF	1.23	1.19	1.22	1.21	0.06
Initial ADIP (% DM)	0.51	0.51	0.52	0.51	0.03
Final ADIP (% DM)	0.87_b	0.73_a	0.78_a	0.87_b	0.07
Ratio of final to initial ADIP	1.71_b	1.42_a	1.52_a	1.71_b	0.17

* Alphabetic subscripts in rows denote statistical difference @ P = 5%.

When the crop was baled with relatively low moisture, the propionic treatment had statistically greater ratios of initial to final ADF and NDF than the control treatment (table 8). When the crop was baled with relatively high moisture, the propionic treatment had a statistically or numerically lower ratio of final to initial ADF than the other treatments (table 9). However, ratio of final to initial NDF was similar for all treatments when baled at high relative moisture (table 9). Because DM loss and fiber concentration are linked (see above), these results seem to confirm the DM loss data (table 3).

Bales treated with propionic acid had a lower level of bound protein than the control treatment at both low and high moisture levels (tables 8 and 9). This is consistent with the propionic treatment having lower temperature in storage (fig. 4). Crop baled at relatively high moisture and treated with inoculant exhibited less damage from excess bale temperature than the control or ventilated bales (table 9), despite the fact that bales from all these treatments exhibited similar in-storage temperature profiles (fig. 4).

Discussion

Effect of Propionic Acid on Bale Preservation

Treating hay with propionic acid is intended to suppress the level of microbial growth. Rotz et al. (1991) treated small square bales of alfalfa hay with propionic acid at a rate of 1 to 1.5% of hay mass when hay was in a moisture range of 19 to 22% (w.b.). Rotz et al. found no significant difference between the treated and control bales in terms of heating, DM loss or quality constituent retention after 30 days in storage. Rotz et al. speculated that the hygroscopic nature of propionic acid caused acid treated hay to be consistently higher in moisture than untreated hay, even after six months in storage. This higher level of crop moisture was also speculated to increase biological activity, which led to similar levels of DM loss despite the presence of the acid preservative. Results were similar here. In only one case did application of propionic acid reduce the level of heating or heat damage to protein (fig. 4 and table 9). In most cases, bales treated with propionic did not have significantly lower DM loss or reduced fiber concentration at removal from storage (tables 4, 5, 8, and 9). In three of the four trials reported here, the final moisture of the propionic treated bales was higher than that of the other treatments. It may be that the application of propionic acid in the range used in these experiments slowed the rate of biological activity, but the higher moisture in these bales extended this activity for a longer time. The slowed rate reduced the level of bale heating and protein damage, but also caused the bale to stay at higher moisture. This sustained biological activity for a longer period, creating similar overall storage losses to the untreated control bales.

Effect of an Inoculant on Bale Preservation

Bacterial inoculants are intended to enhance bacterial growth during the early stages of storage. These bacteria will produce products, such as lactic and propionic acids, which will inhibit the growth of microorganisms. Rotz et al. (1988) inoculated small square alfalfa bales with strains of *Lactobacillus* when bale moisture ranged from 20 to 40% (w.b.). They found that inoculation did not reduce bale heating or storage DM loss and did not improve bale quality or appearance. Tomes et al. (1990) inoculated small square alfalfa bales with strains of *Lactobacillus* and *Bacillus* when bale moisture ranged from 17 to 30% (w.b.). They found inoculation improved hay appearance but had little effect on DM loss and quality compared to untreated bales. Results were similarly mixed in this study. Bale heating characteristics were similar for control and inoculant treated bales (fig. 4, table 2), yet the ratio of final to initial ADIP was lower for the inoculant treated bales (table 9). At bale moistures greater than 25% (w.b.), inoculant treated bales had numerically lower DM loss than control bales (table 2), yet ratios of final to initial ADF and NDF were similar (table 9). At bale moistures in the mid-teens, the inoculant treatment did not reduce DM loss (table 3) or improve fiber concentration (table 8). At the lower moistures, moisture may have been insufficient to promote bacterial growth.

Effect of Ventilation on Bale Preservation

The presence of a vent hole did not significantly improve bale heating characteristics or DM loss compared to the control treatment (tables 2 and 3). However, in three of the four trials, the ventilated bales had numerically lower DM loss than the control (table 3). Compared to the control treatment, fiber concentration was less for the ventilated bales in one trial (table 4), was greater in another (table 8) and similar in the remaining two trials (tables 5 and 9). Evidence of heat damage to proteins was similarly mixed (tables 4, 5, 8, and 9).

Hay at less than 15% moisture (w.b.) is relatively stable and little loss occurs from respiration by bacteria, fungi and yeasts (Rotz and Muck, 1994). The longer hay stays above equilibrium moisture, the longer the period of biological activity (Rotz and Muck, 1994). In this respect, the presence of the vent hole may have tended to reduce the extent of biological activity by allowing the bale to reach equilibrium moisture more quickly than other treatments. However, the rate of respiration for many microorganisms present in baled hay is enhanced by the presence of oxygen. In this respect, the presence of the vent hole may have tended to allow more oxygen to penetrate to the interior of the bale thereby increasing the rate of respiration. The temperature profile taken at various radial positions (fig. 3) shows that the presence of the vent hole promoted air exchange in the interior of the bale.

The presence of a vent hole in small square bales did not reduce heating during storage nor improve bale quality but DM loss and level of bound protein were slightly less in the ventilated bales (Rotz et al., 1993). The work by Rotz et al. and the research in the experiments reported here suggest that ventilating hay bales could offer some reduction in storage losses and improve bale quality. Further work is needed to investigate the size and position of ventilation holes in large square bales that will maximize the positive effect on hay quality.

Conclusions

- Ventilated bales did not heat less in storage than the control treatment. Also, ventilated bales had a similar change in bound protein, indicating similar heat damage to the control. When bale moisture was greater than 25% (w.b.), treatment with 0.8% propionic acid reduced bale heating and produced less heat damage to proteins compared to the control.
- The temperature profile at greater radial distances from the edge of a 12-cm-diameter vent hole was similar to the diurnal variation of ambient temperature, indicating that some heat and air exchange occurred through the vent hole. The amplitude of this diurnal fluctuation in the bale decreased with greater distance from the hole. This diurnal fluctuation phenomenon was not evident in bales with the 8-cm-diameter vent hole.
- None of the preservation techniques significantly reduced DM loss compared to the control. However, in three of four trials, bales with the 12-cm-diameter vent hole had numerically lower DM loss compared to the control. In three of four trials, bales treated with propionic acid had numerically higher DM loss compared to the control. Treatment with inoculant produced numerically lower DM loss than the control in two trials.
- None of the preservation techniques significantly reduced fiber concentration (ADF or NDF) compared to the control.
- Bales treated with propionic acid maintained higher moisture during storage compared to other treatments in three of the four trials. This may have lead to a longer period of biological activity that offset the benefit of suppressed rate of microorganism activity from the acid treatment.
- Increased bale DM loss and reduced quality were related to initial bale moisture. The key to maintaining large square bale quality and keeping DM loss below 4% was baling at moistures below 16% (w.b.).

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NOMENCLATURE

DM	Dry matter
CP	Crude protein
ADF	Acid detergent fiber
NDF	Neutral detergent fiber
ADIP	Acid detergent insoluble protein
MC	Moisture content on a wet basis
w.b.	wet basis
LSD	Least square difference
HDD	Heating degree days greater than 35°C