STORAGE CHARACTERISTICS OF LARGE ROUND ALFALFA BALES: DRY HAY

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ABSTRACT. *Losses of forage dry matter (DM) and quality in large round bales of alfalfa stored outdoors can be substantial. The objective of this research was to determine the effect of wrap type and storage method on the preservation of dry alfalfa bales stored outdoors. Several methods to wrap large round dry hay bales of alfalfa/grass and grass/alfalfa were investigated, including sisal twine (ST), plastic twine (PT), to-edge net wrap (TEN), cover-edge net wrap (CEN), plastic bale covers (BC) and indoor storage (IS). Some outdoor storage treatments were split between storing either directly on the ground or on a well-drained surface. Storage characteristics were quantified by moisture in the outer layer versus time, final moisture distribution, DM loss, and nutrient retention. Storage length was either 5 or 11 months. Net wrap bales consistently had lower moisture in the outer layer and lower DM loss than twine wrapped bales. Net wrapped bales shed more water than twine wrapped bales, so storing on a well-drained surface was important to reduce damage to the bottom of the bale. Average DM loss across all trials was 19.5%, 11.3%, and 7.3% of DM for ST, PT, and TEN/CEN treatments, respectively. Compared to other treatments, DM losses were significantly less for BC and IS bales. Storing on a well-drained surface reduced DM losses for all treatments. Net wrapped bales tended to have better nutrient retention in the outer layer than twine wrapped bales, but nutrient retention in the bale core was unaffected by wrapping or storage treatment. Wrapping with net wrap increased baling productivity by 32% and reduced losses during wrapping by 65% compared to wrapping with twine. Wrapping bales of alfalfa with a mesh net wrap and storing on a well-drained surface will substantially reduce losses of forage DM and quality compared to wrapping bales with twine.*

Keywords. *Alfalfa, Bales, Film warp, Losses, Net wrap, Round bales, Twine.*

In North America, dry hay is typically packaged using three types of bales: small square, large round (LRB), and large square bales. The LRB is the most common way that hay for ruminant animals is packaged and stored in North America because it can be stored outdoors, greatly reducing the cost of storage. Many hay producers also prefer the round baler because it offers high productivity at a much lower cost than a large square baler. The LRB is used to package hay primarily for beef animals but also for young stock and dry cows in the dairy industry and the equestrian market as well.

As originally conceived, the LRB restrained the hay in the bale by wrapping the periphery of the bale with sisal or plastic twine. Since no additional hay can be placed in the bale during wrapping, baling must stop while the bale is wrapped. Even with twine applied by dual twine arms, LRB wrapping time can almost equal the time required to form a bale, resulting in low productivity. Net wrap was introduced on round balers in the late 1980s (Anstey and Ardueser, 1991; Butler, 1992). Net wrap applies a fine plastic mesh to the periphery of the bale. Only a few rotations of the bale are required to wrap the bale with net, compared to 20 to 30 rotations with twine, because the net wrap is applied across the whole bale width at once. Perceived advantages of net compared to twine wrap include greater baling productivity, lower losses during wrapping, better bale integrity during handling and transport, better water shedding ability, and lower outdoor storage losses. Although net wrap offers many advantages, some producers are reluctant to adopt the technology because the wrapping mechanism can increase the initial cost of the baler by 15% to 25%, depending upon bale size. In addition, the cost of wrapping with net wrap compared to twine is about \$1.15 to \$1.60 more per dry metric ton of hay depending on bale size and number of wraps. Net wrapping can only be justified if the additional ownership and operating costs are offset by greater productivity, lower wrapping losses, improved timeliness, and lower storage losses.

Net wrapping was found to increase baling productivity by 5% to 8% when applied to a 1.52 × 1.68 m bale (Taylor, 1995). Numerous researchers (table 1) have studied LRB outdoor storage losses as affected by type of wrap. In general, the research results suggest that wrapping with net reduced storage loss compared to wrapping with twine. The exceptions occurred when precipitation was low (Taylor et

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Table 1. Results from previous published research concerning storage losses of various wrap types.

Reference	Approximate Storage Length (months)	Crop	Approximate Precipitation During Storage (cm)	Twine Type	Approximate Final Bale Moisture (% w.b.)	DM Loss (% of total DM)	
						Net Wrap	Twine Wrap
Taylor et al., 1994	10	Alfalfa	25	Plastic	12	2.8	2.1
Russell et al., 1990	9	Alfalfa / Grass	64	Sisal	18	6.9	11.7
Harrigan and Rotz, 1994[a]	9	Alfalfa	55	Sisal	21	16.3	16.5
Collins et al., 1995[a]	12	Tall Fescue	138	Sisal	_	10.6	18.2
Bledsoe and Bates, 1992	8	Alfalfa / Grass	125	Sisal	18	19.1	23.2

[a] Fixed chamber baler used.

al., 1994) or when low-density bales were formed with a fixed chamber baler (Harrigan and Rotz, 1994). Collins et al. (1995) reported that the depth of severely weathered hay was significantly less for net wrap bales, indicating better water shedding ability. They also reported that a plastic film "bale cover" further reduced the depth of the weathered layer and DM loss compared to net wrap. Russell et al. (1990) reported that net wrap reduced DM loss and the fraction of the hay lost to weathering and that placing bales on a well-drained surface reduced DM loss and the depth of the weathered layer.

The objectives of this research were to determine field loss and productivity differences when wrapping with twine or net and to determine storage characteristics of dry hay bales wrapped with twine, net, or plastic covers and stored outdoors.

Materials and Methods

Experimental Treatments

Four bale wrapping treatments were studied in 2000 in two cuttings: sisal twine (ST), plastic twine (PT), to-edge net wrap (TEN), and cover-edge net wrap (CEN). Bale characteristics and crop conditions at bale formation and total precipitation during storage are listed in table 2. All aspects of the two net wrap materials were the same except the CEN extended about 5 cm over the edge of the bale. All treatments were stored outdoors with the bales placed directly on the ground. In 2001, two additional treatments were used: plastic bale covers (BC) and indoor storage (IS). The four original treatments were used again, but half the bales from each treatment were stored directly on the ground and half were stored on wooden pallets that raised the bales off the ground by about 15 cm. Only CEN bales were stored indoors because it was assumed that wrap type would have no effect on bales not exposed to weathering. BC bales were wrapped with CEN at the time of baling and then wrapped with plastic film (see Storage – 2001).

Productivity and Wrapping Losses

In 2000, six bales each of PT and CEN were formed with a John Deere model 567 baler set to provide bales of 160 cm diameter. The baler monitor was set to provide twine spacing of 8 cm with six end wraps or two and one-half layers of net. The crop was second-cutting dry alfalfa hay at about one-quarter bloom. After each bale had reached the desired diameter, the baler was backed onto ramps that raised the baler 20 cm, allowing a frame with a plastic sheet for catching lost material to be placed under the baler. This frame extended from the rear of the baler to about 20 cm past the front of the baler pick-up. Heavy canvas was placed around the periphery of the baler to prevent wind from displacing crop material as it fell from the baler. The monitor controlled wrapping process was then initiated, and the lost material was collected when wrapping was completed. The lost material was placed in paper bags, weighed, and oven dried at 103°C for 24 h (*ASABE Standards*, 2007) to determine total dry mass lost. The ejected bale was weighed to the nearest 0.5 kg on a 1,800 kg capacity scale. The bales were radially bored twice from either side to a depth of about 50 cm using a 5 cm diameter boring tube. Each of these samples was oven dried at 103°C for 24 h. Baler loss during wrapping was expressed as a fraction of total bale DM.

Baling productivity was determined in separate studies from the wrapping loss. Estimated alfalfa yields for the fields where productivity measurements occurred were 4.1 and 5.4 Mg DM/ha for third cutting in 2000 and second cutting in 2001, respectively. Two windrows from a 4.0 m mower-conditioner were merged by raking. An experienced operator formed bales with the John Deere model 457 (117 × 140 cm) in 2000 and model 567 (150 × 165 cm) in 2001. There were 10 and 12 bales each of PT and CEN formed in 2000 and 2001, respectively. The PT bales had 8 cm twine spacing plus six end wraps, and the CEN bales had two and one-half layers of net. In both years, ground speed ranged between 8 and 9 km/h, and the formation of each bale involved an equal number of turns at the headlands. The bale monitor/controller automatically started the wrapping sequence after the desired bale diameter had been reached and controlled the entire

Table 2. Characteristics of dry hay bales prior to storage and precipitation during storage.

Cutting and Date	Estimated Grass Content (%)	Average Bale Diameter (cm)	Average Initial Bale Moisture (% w.b.)	Average Bale DM Density (kg/m^3)	Total Precipitation During Storage (cm)
First - 2000[a]	10	173	16.3	159	39
Second - 2000[a]	5	170	16.2	174	91
First - 2001[a]	25	157	17.4	178	45
Second - 2001[b]	60	173	9.3	171	82

[a] Crop consisted of mainly alfalfa (one-quarter bloom); grass content was mainly orchardgrass.
[b] Crop was mainly orchardgrass; remainder was alfalfa (one-quarter bloom).

wrapping process. Wrapping time was defined as the time from initiation of the wrapping cycle to the time when hay began to enter the baler for the next bale. Both balers were equipped with a bale ejector so no backing was required. An observer with a stopwatch timed the baling and wrapping processes to the nearest second.

Storage - 2000

First-cutting alfalfa was cut on 3 June and baled on 8 June 2000. Drying conditions were considered good; however, a 10 mm shower occurred on the evening of 4 June. Second-cutting alfalfa was cut on 11 July and baled on 14 July 2000, and drying conditions were considered good with no precipitation.

All the bales were formed with a John Deere model 567 round baler with 157 cm bale width and bale diameter set at about 170 cm. Single windrows were baled in first cutting, and two windrows were merged by raking in second cutting. The baler was operated at about 9 km/h with the belt tension set to maximum. The variable density core option was not activated, so belt tension was the same throughout the bale formation. Two bales each using ST, PT, TEN, and CEN were baled in succession, and this pattern was repeated until eight bales of each treatment were formed. All bales were transported to the storage area and stored under cover the evening of baling. All bales were sampled and stored the following day (i.e., within 24 h of formation).

As the bales were placed into storage, they were weighed to the nearest 0.5 kg using a 1,800 kg capacity scale. The bales were bored twice from either side close the edge of the bale at an approximate 45° angle to the bale radius. Samples were collected to a depth of about 50 cm using a 5 cm diameter boring tube. Two samples each for moisture and nutrient determination were oven dried at 103°C for 24 h and 65°C for 72 h , respectively (*ASABE Standards*, 2007).

The bales were stored directly on a grass surface. Although the site was not appreciably sloped, it was a high spot where water could not accumulate. Bales were placed in two rows running roughly north-south, and there were no trees or structures to shade the bales. The ends of the bales were butted tightly together. The spacing between the two rows was about 3 m. All eight bales of each treatment were grouped together, so there were no interactive effects between wrap types. A sacrificial bale was placed at the ends of both rows and between treatments so that data were collected only on bales in the interior of the row adjacent to bales of similar wrap type.

Bale moisture at a depth of 10 cm was measured on all bales at approximately two-week intervals throughout the summer storage period. A Delmhorst model F-2000 conductance-type moisture sensor was used to probe the bales at 12 different locations on the exposed periphery. The sensor diameter was less than 1 cm, so it did not disrupt bale or wrap integrity. Measurement locations were made at 12 locations on each bale, about 20 cm from the right and left sides at the six angular positions indicated in figure 1.

First-cutting bales were removed from storage on 4 November 2000 after 149 days, and second-cutting bales were removed on 5 July 2001 after 356 days. As they were removed from storage, all bales were weighed as previously described. If a portion of the bale was left on the ground when it was lifted, this material was collected by hand and weighed

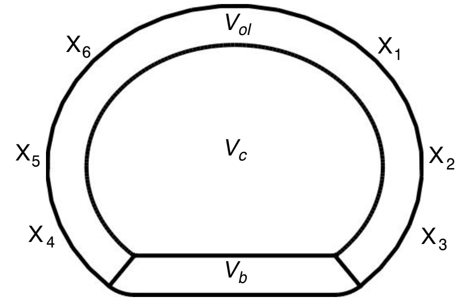

Figure 1. Locations of the volume of the outer layer (V_{ol}), core (V_c), and base (V_b) of the bale used to calculate the volume-adjusted bale moisture for bales removed from storage. Also shown are the six clock positions (X_1 to X_6) on the bale where a conductance moisture sensor was used to estimate moisture of the outer layer.

to the nearest 0.05 kg on a 45 kg capacity scale. Subsamples of the material left on the ground were collected to determine oven dry moisture content. After the bale was weighed, the vertical and horizontal diameters plus bottom length in contact with the ground were measured to the nearest 1 cm on both sides of the bale. Four bore samples for moisture were taken to a depth of about 20 cm, one from each side (X_2 and X_4 in fig. 1) and two from the bottom of the bale. The two side and bottom moistures were averaged and defined as the outer layer and bottom moistures, respectively. Two additional bore samples, one from each side, were taken from a depth of 20 to 50 cm (X_2 and X_4 in fig. 1), and these moistures were defined as the core moisture. All samples for moisture determination were oven dried at 103°C for 24 h.

To determine the DM in the bale after the storage period, the overall volume-adjusted bale moisture was calculated by first using the dimensions described above to calculate the volume of the outer layer, core, and base of the bale (fig. 1). The volume-adjusted moisture of the bale was determined by:

$$M_a = \frac{\left(M_{ol} \cdot V_{ol} + M_c \cdot V_c + M_b \cdot V_b\right)}{V_t} \qquad (1)$$

where *M* is wet basis moisture content, *V* is volume of bale section, and the subscripts indicate the volume-adjusted total (*a*) and the outer layer (*ol*), core (*c*), base (*b*), and total (*t*) volume.

Samples for nutrient determination were bored in a similar fashion, except that no sample was collected from the bottom of the bale. These samples were oven dried at 65°C for 72 h and then analyzed using wet laboratory methods for crude protein (CP), acid-detergent fiber (ADF), neutral-detergent fiber (NDF), and in vitro true digestibility (IVTD) by the University of Wisconsin Department of Agronomy. Samples were analyzed for total N concentration by the Dumas method (AOAC, 1990) with an automated analyzer (model FP-528, Leco Corp., St. Joseph, Mich.). Crude protein concentrations were calculated by multiplying total N by 6.25. Fiber concentrations were determined by the batch procedure outlined by ANKOM Technology Corp. (Fairport, N.Y.). Subsamples (0.25 g each) were analyzed for in vitro true digestibility (IVTD) using rumen fluid from a lactating Holstein cow on a total mixed ration and buffer solution described by Van Soest et al. (1991) with a Daisy II200 in vitro incubator and an ANKOM200 fiber analyzer (ANKOM Technology Corp., Fairport, N.Y.).

A detailed moisture profile using the conductance-type moisture sensor described above was determined when second-cutting bales were removed. The sensor was inserted to a depth of 25 cm on the ends of the bale roughly parallel to its longitudinal axis. Measurements were taken at 5, 10, 15, 20, 30, and 50 cm radial distance from the bale surface and at the approximate center of the bale. Measurements were taken at the 3, 6, 9, and 12 o'clock radii (two horizontal and two vertical radii). Therefore, a total of 50 moisture measurements were made from each bale.

Storage - 2001

For the 2001 trials, baling operations were similar to that described above. First-cutting alfalfa/grass was cut on 6 June and baled on 11 June 2001 (table 2). Drying conditions were considered good; however, a 2 mm shower occurred on 8 June. Second-cutting grass/alfalfa was cut on 4 July and baled on 10 July 2001, and drying conditions were considered excellent with no precipitation.

The baling operation was conducted in the same sequence as described for the 2000 trials except that a total of 12 bales were formed for each treatment. Two additional treatments were added in 2001: IS and BC. The BC bales were wrapped in six layers of 1 mil stretch film using a Hay Wrap spear-type bale wrapper. The plastic film was applied completely around the bale periphery but not on the ends of the bale. All bales were handled and stored in a manner similar to that described for the 2000 trials. However, the ST, PT, TEN, and CEN treatments were split so that half the bales were placed directly on ground (grass surface) and half were stored on wooden pallets that raised the bales about 15 cm. The BC bales were only stored on the ground. The IS bales were stored on a crushed rock surface near the rear of an open-front hay shed so that they were not exposed directly to precipitation or sunlight. The bales stored outdoors were placed in two rows, one on the ground and one on the pallets. All other aspects of the storage scheme were similar to that used in 2000.

Bale moisture was measured using the conductance-type moisture probe on all first and second cutting bales at approximately two-week intervals throughout the summer storage period in a manner similar to that described above. The plastic film was carefully pulled back from the edge of the BC bales to make measurements so that plastic integrity was maintained.

First-cutting bales were removed from storage on 2 November 2001 after 144 days, and second-cutting bales were removed on 24 June 2002 after 349 days. Removal procedures were the same as those used in 2000.

Statistical Analysis

A single-factor analysis of variance was conducted on all the trials to determine statistically significant differences between treatments. A two-way analysis of variance was used to block confounding effects when analyzing data across more than one variable. All statistical differences were based on a least significant difference (LSD) with a probability of 95% (Steel et al., 1996).

Results

Baling Productivity and Field Wrapping Losses

Compared to twine wrapping, net wrapping improved productivity and reduced wrapping losses (table 3). Net wrapping increased baling rate by 32% with either bale size. Time to net wrap the larger bale was only 10% greater than that for the smaller bale because only an additional 2 m of wrap was needed. Time to twine wrap the larger bale was 60% greater than for the smaller bale because an additional 20 m of twine was needed. Therefore, the productivity improvements of net wrap were about the same for both bale sizes even though wrapping represents a smaller fraction of the total harvesting time with the larger bale size. During wrapping, bales were turned approximately four and 25 revolutions with net and twine, respectively, accounting for most differences in crop loss. In addition, net had better surface coverage because it surrounded the bale periphery with a 2 cm square weave compared to the 8 cm spacing of spiral twine coverage.

Taylor (1995) reported that net wrap increased baling productivity by only 8% using an almost identical baler, monitor, and bale size to that used here. The productivity differences between the studies were possibly due to twine spacing, number of end wraps, and operator skill. At current retail prices, net wrapping adds material costs of $0.90 to $1.20 per bale compared to twine wrapping, depending on bale size and number of wraps. The average bale moisture was 13.2% (w.b.), unusually low for July conditions in Wisconsin, so wrapping losses might have been higher than typically expected. If baling with more typical moisture would have reduced losses for both treatments by 50%, then the difference in wrapping losses would have been 1% of total DM. At current retail prices for hay packaged in round bales, the additional harvest of 1% DM would correspond to about $1.10 per bale, almost offsetting the additional material cost of the net wrap. Losses were observed to be mostly leaves, so the real value of the lost material could be expected to greater than $1.10 per bale.

Table 3. Baling productivity and losses of DM for net and twine wrap balers of two different sizes.

Wrap Type	2000[a] 117 cm width × 140 cm diameter: Wrapping Time (s)	Total Baling and Wrapping Time (s)	2001[a] 150 cm width × 165 cm diameter: Wrapping Time (s)	Total Baling and Wrapping Time (s)	Wrapping Loss[b] (% of DM)
Net	20 a	84 a	22 a	172 a	1.0 a
Twine	47 b	111 b	75 b	227 b	2.9 b
LSD[c] (P = 0.05)	3	7	3	8	0.9

[a] Estimated yield was 4.1 and 5.4 Mg DM/ha for third cutting in 2000 and second cutting in 2001, respectively. Two windrows from a 4.0 m mower-conditioner were merged by raking. The twine bales had 8 cm twine spacing plus six end wraps, and the net wrap bales had two and one-half layers of net. In both years, ground speed ranged between 8 and 9 km/h.

[b] Average moisture of bales was 13.2% (w.b.).

[c] Averages within columns followed by different letters are significantly different at the 95% confidence level.

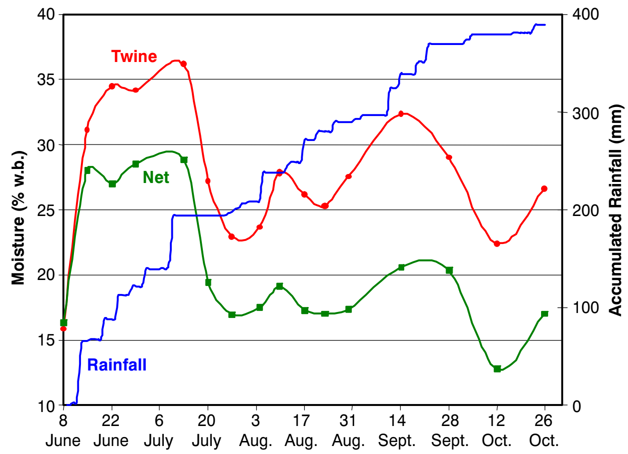

Figure 2. Estimated moisture just below the bale surface of first cutting (2000) alfalfa/grass bales based on a conductance sensor inserted to a depth of 10 cm at 12 different locations on each bale.

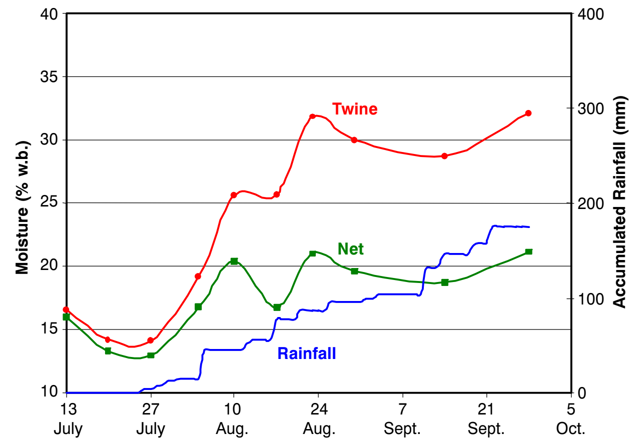

Figure 3. Estimated moisture just below the bale surface of second cutting (2000) alfalfa/grass bales based on a conductance sensor inserted to a depth of 10 cm at 12 different locations on each bale.

Bale Moisture History

There were no significant differences in moisture at 10 cm depth between the ST and PT bales or between TEN and CEN bales in all four trials, so the two twine and two net datasets were combined. Net wrap bales of alfalfa consistently had lower moisture just below the surface than twine wrap bales (figs. 2 to 5). Alfalfa leaves and stems formed a good thatch on net wrapped bales, so only during periods of persistent, heavy rainfall was the outer layer of these bales measured above 20% moisture (e.g., fig. 2). Twine wrapped alfalfa bales had fewer leaves on the surface due to wrapping losses (table 3), so the thatch formed was not as cohesive and the outer layer of these bales was often measured at greater than 20% moisture. Although the BC bales were protected from rain, the moisture at 10 cm depth was often greater than that of the twine wrapped bales (fig. 4 and 5). The plastic film prevented moisture in the bale from leaving the bale, so there was condensation on the inside surface of the film. When bales were formed with fine-stemmed grass, it was observed that an excellent thatch was formed on all bales regardless of wrap type. The excellent thatching and the very low initial moisture (table 2) resulted in very little difference in the moisture of the outer layer between treatments during the early storage period (fig. 5).

When removed from storage, net wrapped bales generally had lower moisture to a depth of 20 cm than twine wrapped bales on both sides and the top of the bale (tables 4 to 6). The moisture at the bottom of bales stored on the ground was quite high, with the net wrapped bales generally having higher moisture than twine wrapped bales through the first 15 cm of the bottom (tables 4 and 6). When alfalfa bales were stored on pallets, there was no difference in moisture at the bottom of the bale between the net and twine treatments (table 5). When grass bales were stored on pallets, the net wrapped bales had a slight trend toward higher moisture at the bottom, probably because these bales had excellent water shedding ability, which brought more water to the bottom of the bale (table 6). The condensation observed in the BC bales only affected the hay moisture in the outer 5 cm of the alfalfa bales (table 5).

The data from the conductance moisture sensor (figs. 2 to 4; tables 4 to 6) and the oven dry moisture of the outer layer of the bale (tables 7 and 8) suggest that the net wrapped bales

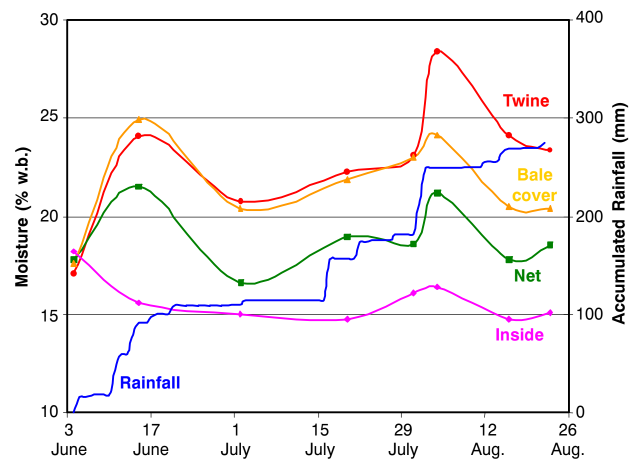

Figure 4. Estimated moisture just below the bale surface of first cutting (2001) alfalfa/grass bales based on a conductance sensor inserted to a depth of 10 cm at 12 different locations on each bale.

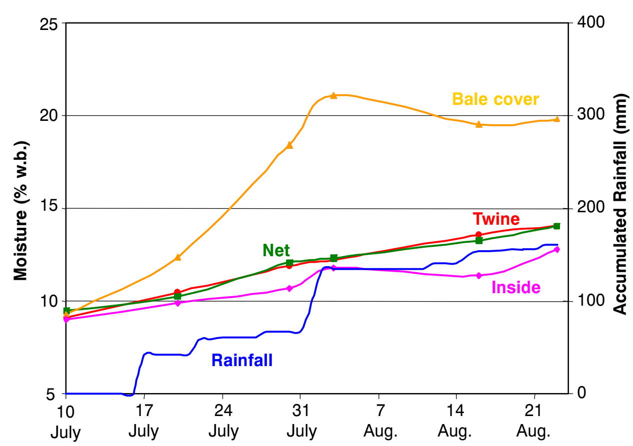

Figure 5. Estimated moisture just below the bale surface of second cutting (2001) grass/alfalfa bales based on a conductance sensor inserted to a depth of 10 cm at 12 different locations on each bale.

were better at shedding water than the twine wrapped bales. However, numerous research results have found that there was no difference in the moisture of the outer layer between twine and net wrapped bales (Bledsoe and Bales, 1992;

Table 4. Moisture profile (% w.b.) of second-cutting alfalfa/grass bales formed in July 2000. Wet basis moisture estimated using a conductance sensor at time bales were removed from storage after 356 days.

Position on Bale	Wrap Type[a]	Radial Position from Edge of Bale (cm) 5	10	15	20	30	50
East	ST/PT	35.8 a	35.1 a	30.8 a	24.9 a	19.7	17.4
	TEN/CEN	19.0 b	19.7 b	20.3 b	20.2 b	18.5	18.9
	LSD[b] (P = 0.05)	4.3	3.8	3.8	2.1	1.2	1.6
West	ST/PT	24.8 a	25.3 a	24.5 a	22.2 a	18.9	18.4
	TEN/CEN	18.7 b	20.8 b	21.2 b	19.3 b	17.7	18.5
	LSD[b] (P = 0.05)	5.5	4.3	3.2	2.7	2.1	1.0
Top	ST/PT	21.0 a	24.0 a	22.1 a	20.8 a	19.0	18.0
	TEN/CEN	15.8 b	18.3 b	18.6 b	17.9 b	18.5	16.4
	LSD[b] (P = 0.05)	2.7	3.3	2.5	1.7	1.5	1.1
Bottom	ST/PT	38.3 a	34.0 a	30.6	26.9	21.6	19.8
	TEN/CEN	39.7 b	37.0 b	32.6	26.7	21.6	19.4
	LSD[b] (P = 0.05)	1.0	2.2	3.3	2.7	1.9	1.5
Sides[c]	East	27.4 b	27.4 b	25.6 b	23.6 b	19.1	18.1
	West	21.8 a	23.1 a	22.8 a	20.8 a	18.3	18.4
	LSD[b] (P = 0.05)	2.5	3.6	2.7	1.8	1.9	1.5

[a] Sisal twine (ST), plastic twine (PT), to-edge net wrap (TEN), or cover-edge net wrap (CEN). Data from ST and PT and from TEN and CEN are averaged together.
[b] Averages in columns followed by different letters are significantly different at the 95% confidence level.
[c] Data from twine and net bales are pooled and analyzed using two-way analysis of variance.

Table 5. Moisture profile (% w.b.) of first-cutting alfalfa/grass bales formed in June 2001. Wet basis moisture estimated using a conductance sensor at time bales were removed from storage after 144 days.

Position on Bale	Wrap Type[a]	Radial Position from Edge of Bale (cm) 5	10	15	20	30	50	Center
East[b]	ST/PT	25.2 c	24.7 c	22.4 c	18.6 b	14.7 b	13.8 bc	13.6 b
	TEN/CEN	16.6 b	18.1 b	16.8 b	13.4 a	12.1 a	11.6 a	12.4 a
	BC	21.7b c	16.7 b	15.7 b	14.3 a	12.6 a	13.1 ab	12.9 ab
	IS	9.4 a	9.7 a	10.3 a	11.5 a	13.1 a	14.7 b	12.1 a
	LSD[c] (P = 0.05)	6.5	6.1	5.2	3.3	1.8	1.5	0.9
West[b]	ST/PT	22.8 c	22.4 c	22.5 c	19.9 c	15.0 c	12.5 b	
	TEN/CEN	12.3 ab	13.4 ab	14.7 b	14.2 b	13.9 bc	13.3 b	
	BC	16.7 b	15.7 b	15.3 b	13.2 b	12.9 b	13.5 b	
	IS	9.0 a	9.2 a	9.2 a	9.3 a	10.1 a	10.4 a	
	LSD[c] (P = 0.05)	4.9	4.2	4.1	3.6	1.8	1.4	
Top[b]	ST/PT	17.5 b	16.9 b	15.9 b	15.1 b	13.5	13.4 ab	
	TEN/CEN	11.3 a	12.1 a	12.1 a	12.7 a	12.4	12.4 a	
	BC	20.2 c	18.5 b	17.4 c	15.3 b	13.6	13.6 ab	
	IS	11.9 a	12.2 a	13.2 a	13.8 ab	14.0	14.4 b	
	LSD[c] (P = 0.05)	2.3	2.1	1.9	1.9	1.9	1.8	
Bottom - ground	ST/PT	35.1 c	27.4 c	21.8 c	17.4 c	13.4 bc	14.0 b	
	TEN/CEN	25.8 b	23.6 b	19.7 bc	15.6 bc	15.3 c	14.7 b	
	BC	35.6 c	22.6 b	18.6 b	14.8 b	12.8 ab	13.7 b	
	IS	16.6 a	14.4 a	12.1 a	11.9 a	11.6 a	11.4 a	
	LSD[c] (P = 0.05)	6.1	3.7	2.9	2.5	2.0	1.2	
Bottom - pallet	ST/PT	20.9	18.0	16.3	15.5	14.0	13.8	
	TEN/CEN	19.8	17.4	16.5	14.9	13.1	12.5	
	LSD[c] (P = 0.05)	4.4	3.4	2.9	2.7	2.3	2.1	
Bottom[d]	Ground	30.5 b	25.5 b	20.7 b	16.5	15.4	14.4	
	Pallet	20.3 a	17.7 a	16.5 a	15.3	13.5	13.1	
	LSD[c] (P = 0.05)	2.6	3.6	2.8	2.3	1.9	1.7	
Sides[e]	East	20.6	21.3 b	19.5	15.9	13.5	12.7	
	West	17.4	17.8 a	18.5	16.9	14.3	12.8	
	LSD[c] (P = 0.05)	3.7	3.4	3.1	2.3	1.1	0.9	

[a] Sisal twine (ST), plastic twine (PT), to-edge net wrap (TEN), cover-edge net wrap (CEN), bale cover (BC) or stored indoors (IS). Data from ST and PT and from TEN and CEN are averaged together.
[b] Data from bales on ground and pallets are pooled and analyzed using two-way analysis of variance.
[c] Averages in columns followed by different letters are significantly different at the 95% confidence level.
[d] Data from bales on ground or on pallets are pooled and analyzed using two-way analysis of variance.
[e] Data from twine and net bales stored outdoors are pooled and analyzed using two-way analysis of variance.

Table 6. Moisture profile (% w.b.) of second-cutting grass/alfalfa bales formed in July 2001. Wet basis moisture estimated using a conductance sensor at time bales were removed from storage after 349 days.

Position on Bale	Wrap Type[a]	Radial Position from Edge of Bale (cm) 5	10	15	20	30	50	Center
East[b]	ST/PT	22.2 c	23.5 d	21.9 c	19.7 c	15.8 b	12.2 b	11.0 b
	TEN/CEN	17.8 b	20.5 c	20.4 c	18.9 c	17.6 c	14.2 c	12.0 c
	BC	15.4 b	15.4 b	14.7 b	14.9 b	11.6 a	10.0 a	9.8 a
	IS	11.1 a	10.9 a	10.5 a	10.3 a	10.4 a	9.9 a	9.4 a
	LSD[c] (P = 0.05)	3.3	2.5	2.0	1.9	1.6	1.0	0.6
West[b]	ST/PT	16.9 b	19.7 b	16.6 c	14.8 c	13.2 b	11.0 b	
	TEN/CEN	12.6 a	13.7 a	14.1 b	13.5 b	13.8 bc	12.0 c	
	BC	12.6 a	14.5 a	14.9 bc	14.9 c	15.3 c	14.1 d	
	IS	11.9 a	12.2 a	11.5 a	11.5 a	10.8 a	10.1 a	
	LSD[c] (P = 0.05)	3.2	3.1	1.8	1.2	1.7	0.7	
Top[b]	ST/PT	12.6 b	14.1 c	13.8 c	13.4 bc	12.6 b	11.0 b	
	TEN/CEN	12.2 b	12.8 b	12.9 bc	12.7 b	12.0 b	10.8 b	
	BC	11.9 b	12.1 b	12.1 b	14.2 c	12.0 b	11.8 c	
	IS	10.5 a	10.3 a	10.8 a	10.7 a	10.1 a	9.7 a	
	LSD[c] (P = 0.05)	1.2	1.2	1.2	1.4	0.9	0.7	
Bottom - ground	ST/PT	35.8 c	20.3 b	16.5 b	14.9 b	13.1 b	10.8 ab	
	TEN/CEN	32.3 b	27.2 c	22.0 c	18.9 c	16.9 d	13.4 c	
	BC	32.1 b	25.0 c	17.7 b	15.1 b	14.3 bc	11.3 b	
	IS	21.0 a	15.9 a	13.6 a	12.1 a	10.8 a	10.0 a	
	LSD[c] (P = 0.05)	3.0	3.0	1.7	1.9	1.5	1.1	
Bottom - pallet	ST/PT	23.9	20.8 a	17.5 a	16.6	14.1 a	11.8 a	
	TEN/CEN	28.0	25.0 b	21.0 b	18.5	16.5 b	13.2 b	
	LSD[c] (P = 0.05)	4.7	3.9	3.0	2.6	1.9	1.3	
Bottom[d]	Ground	33.6 b	24.7	20.0	17.4	15.5	12.5	
	Pallet	25.7 a	23.1	19.4	17.6	15.4	12.5	
	LSD[c] (P = 0.05)	4.5	3.8	2.7	2.3	1.8	1.3	
Sides[e]	East	19.7 b	21.8 b	21.1 b	19.3 b	16.8 b	13.3 b	
	West	14.5 a	16.3 a	15.2 a	14.1 a	13.5 a	11.6 a	
	LSD[c] (P = 0.05)	2.3	2.0	1.3	1.1	1.1	0.6	

[a] Sisal twine (ST), plastic twine (PT), to-edge net wrap (TEN), cover-edge net wrap (CEN), bale cover (BC) or stored indoors (IS). Data from ST and PT and from TEN and CEN are averaged together.
[b] Data from bales on ground and pallets are pooled and analyzed using two-way analysis of variance.
[c] Averages in columns followed by different letters are significantly different at the 95% confidence level.
[d] Data from bales on ground or on pallets are pooled and analyzed using two-way analysis of variance.
[e] Data from twine and net bales stored outdoors are pooled and analyzed using two-way analysis of variance.

Table 7. Moisture distribution, DM loss, and ground contact of first and second cutting alfalfa/grass bales formed June and July 2000 and removed from storage after 149 and 356 days, respectively.

	Wrap Type[a]	Initial Bale MC (% w.b.)	DM Loss (% of total)	Moisture Out of Storage (% w.b.) Outer Layer	Core	Base	Vol-Adj Total[b]	Ground Contact[c] (cm)
First cutting	ST	15.0 a	16.3 c	20.9 c	17.1 c	33.2 c	18.5 c	144 d
	PT	16.6 b	9.0 b	18.2 b	16.0 b	25.8 a	17.4 b	126 b
	TEN	16.3 ab	6.9 a	17.4 ab	15.1 a	34.8 c	17.0 ab	134 c
	CEN	17.1 b	6.7 a	17.0 a	15.2 a	30.8 b	16.6 a	114 a
	LSD[d] (P = 0.05)	1.5	1.9	1.0	0.6	2.2	0.6	3
Second cutting	ST	16.6	22.9 c	33.1 b	16.4 b	43.1 c	28.6 c	141 c
	PT	16.5	15.1 b	31.4 b	16.2 b	29.1 a	25.4 bc	111 b
	TEN	16.4	7.9 a	21.1 a	14.9 a	38.4 bc	21.6 ab	112 b
	CEN	15.4	8.1 a	19.6 a	15.7 ab	34.7 b	20.4 a	98 a
	LSD[d] (P = 0.05)	1.5	3.2	6.9	1.0	5.4	3.9	9

[a] Sisal twine (ST), plastic twine (PT), to-edge net wrap (TEN), or cover-edge net wrap (CEN).
[b] Volume-adjusted total.
[c] Width of the bottom of bale in contact with the ground.
[d] Averages in columns followed by different letters are significantly different at the 95% confidence level.

Harrigan and Rotz, 1994; Russell et al., 1990; Taylor et al., 1994). Some of this research was conducted under very arid (Taylor et al., 1994) or very wet (Bledsoe and Bales, 1992) conditions, so differences in outer layer moisture could have

Table 8. Moisture distribution, DM loss, and ground contact of first and second cutting alfalfa/grass and grass/alfalfa bales formed June and July 2001 and removed from storage after 144 and 349 days, respectively.

	First Cutting							Second Cutting						
			Moisture Out of Storage (% w.b.)							Moisture Out of Storage (% w.b.)				
Wrap Type[a]	Initial Bale MC (% w.b.)	DM Loss (% of total)	Outer Layer	Core	Base	Vol-Adj[b] Total	Ground Contact (cm)[c]	Initial Bale MC (% w.b.)	DM Loss (% of total)	Outer Layer	Core	Base	Vol-Adj[b] Total	Ground Contact (cm)[c]
Stored on Ground														
ST	16.5	14.6 e	20.3 bcd	17.0 b	37.9 d	21.8 d	90 b	9.2	24.3 d	20.7 c	14.7 cd	39.6 d	20.9 d	132 d
PT	17.7	9.9 d	21.9 d	18.4 c	21.4 b	20.6 c	80 ab	9.1	11.2 c	20.8 c	14.6 cd	24.8 b	19.1 cd	94 b
TEN	18.3	7.6 c	19.3 c	16.6 ab	27.6 c	19.7 bc	110 c	9.8	6.7 b	15.1 ab	14.2 c	29.8 c	17.0 b	103 c
CEN	17.5	7.2 bc	18.8 b	16.2 a	26.6 c	18.9 b	81 ab	9.7	7.1 b	17.2 b	15.0 d	29.1 c	17.7 b	96 bc
BC	17.6	5.9 b	20.8 cd	16.9 b	35.6 d	21.4 cd	73 a	9.3	3.1 a	14.8 a	13.3 b	40.6 d	18.7 bc	90 ab
IS	18.2	2.0 a	16.7 a	16.2 a	18.0 a	16.7 a	80 ab	9.0	1.8 a	13.8 a	12.3 a	17.8 a	13.7 a	85 a
LSD[d] (P = 0.05)	1.8	1.4	1.8	0.6	3.0	1.0	14	0.7	1.5	2.2	0.6	2.6	1.3	8
Stored on Pallets														
ST	17.1	8.2 b	22.0 b	16.0	17.8 a	19.3 bc	90 b	9.0	11.6 c	16.1 a	14.5	20.9 ab	16.3	117 d
PT	17.0	7.5 b	20.9 b	16.0	18.5 ab	19.6 c	72 a	8.8	8.5 b	17.5 b	13.8	19.5 a	16.4	91 b
TEN	18.4	6.0 ab	17.4 a	16.0	21.2 c	17.5 ab	98 b	9.2	6.4 ab	15.4 a	14.2	23.8 bc	16.2	109 c
CEN	16.9	4.9 a	16.9 a	15.5	20.9 bc	16.9 a	72 a	9.5	5.8 a	16.2 a	14.0	26.6c	16.5	85 a
LSD[d] (P = 0.05)	2.0	2.5	2.3	1.0	2.6	1.9	11	0.6	2.2	1.2	1.1	4.0	1.9	10

[a] Sisal twine (ST), plastic twine (PT), to-edge net wrap (TEN), cover-edge net wrap (CEN), bale cover (BC), or stored indoors (IS).
[b] Volume-adjusted total.
[c] Width of the bottom of bale in contact with the ground or the pallet.
[d] Averages in columns followed by different letters are significantly different at the 95% confidence level.

been masked by extreme conditions. Other differences affecting thatch effectiveness might include size of stem, leafiness, type of baler, bale density, type of net wrap, and twine spacing. The bi-weekly moisture sensor data (figs. 2 to 4) and the moisture profile and bore samples collected at removal from storage (tables 4 to 8) show a consistent trend for lower moisture in the outer layer of net wrapped bales. When the crop was predominantly fine-stemmed grass, the water shedding advantage of the net wrap was less apparent. However, the moisture of the bales after almost a year in storage still favored the net wrapped treatments (table 8).

Independent of wrap type, the moisture tended to be less on the bale's west side compared to the east side, and less on the top of the bale compared to the sides (tables 4 to 6). The ambient temperature is typically lower in the morning when the sun's radiant energy is striking the bales east side, so less evaporation occurred on the east side.

DM Loss and Nutrient Composition

In almost all cases, net wrap bales had significantly lower DM loss during storage than twine wrapped bales (tables 7 and 8). When stored on ground, ST bales had greater DM loss than PT bales in all trials, primarily because the sisal twine rotted during storage. When this occurred, the ST bales lost integrity, allowing greater moisture penetration, and created more unrecoverable hay at the base of the bale. For all treatments, any hay not recovered when a bale was raised from storage was considered part of the DM loss. When bales were stored on pallets, the sisal twine had fewer tendencies to rot, greatly decreasing DM loss (table 8). Averaged across all trials where bales were stored on the ground, net wrapped bales had about 63% and 35% lower DM losses than ST and PT bales, respectively. There were no significant differences in DM loss between CEN and TEN bales, but CEN bales had significantly smaller ground contact length than TEN bales. Net wrapped bales generally had significantly lower moisture in the outer layer than twine wrapped bales (tables 7 and 8), contributing to lower DM loss with net wrap bales. When stored on ground, the TEN and CEN treatments consistently had significantly higher moisture in the base than the PT treatment. The superior water shedding ability of the net treatments (figs. 1 to 3) was partially offset by water not being able to drain away from the base of the net wrapped bales when stored on ground. The moisture differential between net wrapped and PT bales averaged 6.2 and 4.1 percentage units for bales stored on the ground and pallets, respectively. Storing bales on the well-drained surface of the pallets reduced DM losses for all treatments, although not always significantly (tables 7 and 8). However, when stored on pallets, net wrapped bales still had 45% and 28% lower DM loss than ST and PT wrapped bales, respectively. Huhnke (1990a, 1990b, 1993) reported lower losses with LRB stored on pallets.

Storing bales indoors significantly reduced final moisture and, therefore, DM loss compared to all other treatments (tables 7 and 8). The BC treatment had significantly lower DM loss than all other treatments stored on the ground (tables 7 and 8). Huhnke et al. (1992) reported lower losses with LRB covered with plastic. With this treatment, the BC film prevented rain from penetrating the bale and leaching soluble nutrients, which lowered potential DM loss compared to other treatments. It was observed that the condensation of moisture at the interface between the hay and film caused many large patches of green algae and black mold, which reduced the aesthetic appeal of these bales.

For bales stored on the ground, net wrapped bales had consistently lower DM loss than twine wrapped bales (tables 7 and 8). Average DM loss across all trails for bales stored on the ground was 19.5%, 11.3%, and 7.3% of DM for ST, PT, and net treatments, respectively. This is consistent

Table 9. Nutritional constituent retention for first and second cutting alfalfa/grass bales formed June and July 2000 and removed from storage after 149 and 356 days, respectively.

Wrap Type[a]	Into Storage (% of total DM)				Out of Storage (Nutrient Retention Ratio[b])							
	Average of Outer Layer and Core				Bale Outer Layer				Bale Core			
	CP	ADF	NDF	IVTD	CP	ADF	NDF	IVTD	CP	ADF	NDF	IVTD
First Cutting												
ST	20.2	35.2	48.2	70.6	1.07	1.20 c	1.25 b	0.92 a	1.03	1.05	1.07	0.99
PT	20.0	35.0	47.6	70.5	1.07	1.16 bc	1.18 ab	0.93 ab	1.01	1.04	1.05	0.99
TEN	19.8	35.7	48.3	70.2	1.06	1.11 ab	1.11 a	0.96 bc	1.03	1.05	1.08	0.99
CEN	20.1	35.0	49.0	70.5	1.05	1.07 a	1.10 a	0.98 c	1.03	1.03	1.04	1.00
LSD[c] (P = 0.05)	1.6	2.1	3.5	1.8	0.09	0.07	0.08	0.03	0.08	0.06	0.06	0.02
Second Cutting												
ST	19.2	33.6 a	44.5 a	71.5 ab	1.08 ab	1.28 b	1.33 b	0.83 a	1.01	1.13	1.16 b	0.96
PT	18.2	35.2 ab	46.9 b	70.1 a	1.13 b	1.24 ab	1.27 ab	0.85 a	1.01	1.10	1.12 ab	0.97
TEN	19.1	34.7 ab	43.2 a	72.9 b	1.05 ab	1.23 ab	1.18 a	0.90 b	0.95	1.12	1.15 ab	0.96
CEN	18.3	36.0 b	47.5 b	70.2 a	1.01 a	1.19 a	1.22 a	0.89 b	0.98	1.09	1.09 a	0.97
LSD[c] (P = 0.05)	1.4	2.0	2.3	2.0	0.10	0.08	0.09	0.03	0.06	0.06	0.06	0.03

[a] Sisal twine (ST), plastic twine (PT), to-edge net wrap (TEN), cover-edge net wrap (CEN), bale cover (BC), or stored indoors (IS).
[b] Ratio of constituent value out of storage to value into storage.
[c] Averages in columns followed by different letters are significantly different at the 95% confidence level.

Table 10. Nutritional constituent retention for first and second cutting alfalfa/grass and grass/alfalfa bales formed June and July 2001 and removed from storage after 144 and 349 days, respectively.

Wrap Type[a]	Into Storage (% of total DM)				Out of Storage (Nutrient Retention Ratio[b])							
	Average of Outer Layer and Core				Bale Outer Layer				Bale Core			
	CP	ADF	NDF	IVTD	CP	ADF	NDF	IVTD	CP	ADF	NDF	IVTD
First Cutting												
ST	14.9	33.8 ab	55.7	71.4 abc	1.03	1.12 b	1.11 c	0.97 ab	1.01 ab	1.04	1.05	1.01
PT	14.4	35.0 ab	56.1	70.7 ab	1.04	1.09 b	1.10 bc	0.96 a	1.04 b	1.01	1.02	1.02
TEN	14.4	35.0 ab	56.9	70.3 a	1.07	1.06 ab	1.05 abc	1.01 c	1.00 ab	1.04	1.04	1.01
CEN	13.5	35.5 b	57.6	70.0 a	1.09	1.06 ab	1.07 abc	1.00 bc	1.02 ab	1.03	1.03	1.00
BC	14.2	33.9 ab	55.6	72.6 bc	1.04	1.05 ab	1.04 ab	0.99 abc	1.00 ab	1.00	1.01	1.00
IS	14.0	33.6 a	55.9	72.8 c	1.01	1.01 a	1.03 a	1.00 abc	0.95 a	1.07	1.06	0.99
LSD[c] (P = 0.05)	3.6	1.7	6.7	1.9	0.09	0.07	0.06	0.03	0.07	0.07	0.06	0.03
Second Cutting												
ST	17.9 a	29.3 c	45.8	77.9	1.04 b	1.07	1.14 b	0.95 a	1.02	1.01	1.09	0.99
PT	18.9 ab	28.0 bc	46.5	78.4	1.02 ab	1.10	1.14 b	0.95 a	0.96	1.05	1.07	0.99
TEN	19.4 b	26.1 a	44.2	78.9	0.98 ab	1.06	1.05 a	0.98 b	0.94	1.08	1.05	0.98
CEN	18.9 ab	27.8 abc	46.3	78.2	1.03 ab	1.04	1.05 a	0.98 b	0.95	1.04	1.02	0.98
BC	19.3 b	28.2 bc	45.1	78.9	0.95 a	1.03	1.06 ab	0.99 bc	0.94	1.03	1.04	0.98
IS	18.9 ab	27.4 ab	45.6	77.7	1.01 ab	1.03	1.03 a	1.01 c	0.95	1.03	1.04	0.98
LSD[c] (P = 0.05)	1.0	1.8	3.3	1.3	0.08	0.08	0.08	0.02	0.08	0.07	0.07	0.02

[a] Sisal twine (ST), plastic twine (PT), to-edge net wrap (TEN), cover-edge net wrap (CEN), bale cover (BC), or stored indoors (IS).
[b] Ratio of constituent value out of storage to value into storage.
[c] Averages in columns followed by different letters are significantly different at the 95% confidence level.

with the results of some other researchers (table 1). Where differences between DM losses were previously reported, net wrapping reduced storage losses by about 30% (table 1).

There were some initial compositional differences between treatments, but they were generally minor (tables 9 and 10). The 2001 data from the bales stored on the ground and pallets were pooled because analysis was performed only on samples taken radially from either side of the bale where ground contact would have no affect on nutrient retention. At the core of the bales, there were generally no significant differences in nutrient retention between treatments for all four trials. Any statistical differences were likely due to experimental error rather than identifiable trends. The core moisture of all treatments was often below 17% at the time of removal from storage (tables 7 and 8), which limited biological activity and change in nutrient composition. The nutrient retention ratios were generally closer to one for hay at the core than in the outer layer.

Net wrapped bales tended to have better nutrient retention in the bale outer layer than twine wrapped bales (tables 9 and 10), which was consistent with the DM loss. However, the differences in nutrient retention were not as great as those for DM loss and final moisture (tables 7 and 8). Other researchers also found that although there was a significant difference in DM loss, there was only a trend for nutrient composition to favor the net wrapped bales (Bledsoe and Bales, 1992;

Harrigan and Rotz, 1994; Russell et al., 1990). The nutrient retention in the outer layer of BC bales was similar to that of net wrapped bales. The nutrient retention ratio in the outer layer was generally closer to one for IS bales than for other treatments.

Summary

Wrapping with mesh net wrap increased baling productivity by 32% and reduced losses during wrapping by 65% compared to wrapping with twine. Losses were observed to be mainly alfalfa leaves.

Net wrapped alfalfa bales shed rainfall better than twine wrapped bales, so the moisture in the outer layer of these bales was often below 20% (w.b.) during the early storage period, while twine wrapped bales were often above this moisture. After 5 or 11 months of outdoor storage, the outer layer of twine wrapped alfalfa bales was at higher moisture than net wrapped bales, but the opposite was true at the base of the bale in contact with the ground. There were fewer differences in the moisture of the outer layer between wrap types when the crop was a fine-stemmed grass. Storing bales on pallets reduced moisture in the base of the bale by 3 and 5 percentage units for plastic twine and net wrapped treatments, respectively. Moisture in the outer layer was lower on the west-facing side and top of the bale.

Net wrap preserved DM in the bale better than twine wrap, and storing bales indoors preserved DM better than all outdoor storage treatments. Average DM loss across all four trails was 19.5%, 11.3%, 7.3%, and 7.3% of DM for ST, PT, TEN, and CEN treatments, respectively. In the two trials that included the BC and IS treatments, average DM loss for bales stored on soil was 19.5%, 10.6%, 7.2%, 7.2%, 4.5%, and 1.9% of DM for ST, PT, TEN, CEN, BC, and IS, respectively. Storing on pallets reduced overall DM loss across all treatments by 4 percentage units.

Nutrient retention in the outer layer tended to be better for net compared to twine wrapped bales, with indoor storage producing the best retention. Nutrient composition of the core of the bales was generally unaffected by wrapping treatment.

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Notation

ADF = acid detergent fiber
BC = plastic film bale cover
CP = crude protein
CEN = cover-edge mesh net wrap
DM = dry matter
IVTD = in-vitro true digestibility
IS = in-barn storage
LSD = least significant difference
LRB = large round bale
MC = moisture content
NDF = neutral detergent fiber
PT = plastic twine wrap
ST = sisal twine wrap
TEN = to-edge mesh net wrap
w.b. = wet basis