REDUCING BALER LOSSES IN ARID CLIMATES BY STEAM RE-HYDRATION

K. J. Shinners, W. M. Schlesser

ABSTRACT. *Low-pressure steam was directed onto alfalfa hay at the baler pick-up and pre-compression chamber to reduce leaf loss typically associated with daytime baling in arid climates. The steam quickly softened plant tissue, resulting in reduced losses and greater bale density. Both large square and 3-tie balers were used to bale dry hay during the day with steam re-hydration and at night when dew re-hydration was apparent. Compared to baling with dew re-hydration, steam re-hydration significantly reduced baler losses by an average of 58% (1.2% to 0.5%, respectively) for large square balers and 43% (0.7% to 0.4%, respectively) for 3-tie balers. Although not quantified, visual observation of steam re-hydrated alfalfa bales indicated that leaf retention on the stems was superior to that of bales formed with dew re-hydration. Compared to bales formed with dew re-hydration, steam re-hydration increased bale density by an average of 20% and 30% for large and 3-tie bales, respectively. Bale nutrient composition was not affected by re-hydration method. Diesel fuel use for steam generation typically varied between 3.2 and 4.2 L/Mg of hay and water use varied between 38 and 50 L/Mg of hay.*

Keywords. *Alfalfa, Baling, Bale density, Leaf loss, Hay quality.*

In the arid western regions of the United States, alfalfa is typically grown by commercial hay producers and sold as a commodity. Dairy producers set a minimum hay quality threshold to ensure maximum animal output. Low-quality hay produced because of weather-damage, over-maturity, or leaf loss has much less demand and is sold at greatly reduced prices, often in the range of 25% to 35% less than high-quality hay (Orloff and Putnam, 2010).

Weather conditions in this region are often so dry that hay becomes over-dry and very brittle. Leaf loss from a large square baler roughly doubled when alfalfa hay was baled at 14% compared to 22% moisture (Shinners et al., 1996). When hay is baled very dry and under low humidity, leaves are not only lost, but many of the captured leaves are crushed into a fine powder which is easily lost during feed preparation and mixing (Orloff and Mueller, 2008; Thomas, 2009). To overcome these problems, hay grown in this climate is typically baled when it has been slightly re-hydrated from the accumulation of dew during nighttime or early morning hours (Orloff et al., 1995).

Baling with dew re-hydration is not ideal. Often adequate dew will not occur for several days at a time, causing delays in harvest which increases risks of weather-related losses, increases the time between cuttings, delays irrigation and crop re-growth, and can increase traffic damage to alfalfa re-growth at baling. McGourty et al. (1977) reported yield losses of up to 20% in subsequent cuttings when baling was delayed eight days. Dew formation often occurs late at night, which makes scheduling labor difficult and the baling season arduous (Lowery, 1972). The window when dew conditions are optimum is often small, so producers typically are forced to bale when there is too little or too much dew in an effort to maintain productivity (Orloff et al., 1995). Hay producers also must over-capitalize with equipment to have sufficient daily productivity to harvest the crop during the small harvest window (Lowery, 1972). A system that re-hydrates very dry hay would allow baling during daytime hours, improve labor scheduling and efficiency, increase the daily harvesting window, and increase the quantity of high-quality hay produced.

Hay producers in arid regions have tried spraying a mist of water on the windrow ahead of the baler or at the baler pick-up to re-hydrate brittle alfalfa (Orloff et al., 1995). However, these systems have not been widely adopted because water droplets are too large to achieve uniform coverage throughout the windrow. Water is more likely to evaporate than be absorbed by plant tissue because of natural barriers to water movement through the epidermis. Also, the absorption time is variable based on such factors as cutting, maturity, conditioning level and ambient conditions, so matching the time between water application and baling is difficult (Orloff et al., 1995). Finally, application of water to the windrow ahead of the baler requires an added operation, increasing total baling costs. An alternative system of re-hydration has been proposed that uses steam applied at the baler pick-up (Maher, 1986;

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The authors are **Kevin J. Shinners, ASABE Member,** Professor and **Walter M. Schlesser, ASABE Member,** former Graduate Research Assistant, Department of Biological Systems Engineering, University of Wisconsin, Madison, Wisconsin. **Corresponding author:** Kevin J. Shinners, 460 Henry Mall; Madison, WI 53706; phone: 608-263-0756; e-mail: kjshinne@wisc.edu.

Maher et al., 1989; Staheli, 1998; Staheli West, 2013). Low-pressure steam is injected into the windrow from above and below as it is picked up and moved into the baler pre-compression chamber. For a given spray volume, small droplet size produces greater surface area, resulting in greater absorption rate. The small droplet size and energy of the steam allows it to be easily absorbed, softening plant tissue quickly. Steam is also less dense than air so it won't settle as quickly as water vapor and it has much greater volume than water vapor so more complete coverage of the incoming hay stream is possible.

Steam re-hydration of hay will naturally cause the bale temperature to increase due to the steam temperature. Excess heating can lead to reactions where proteins and amino acids combine with plant sugars to form a polymer resembling lignin (Yu, 1977; Pitt, 1990). This phenomenon is quantified by acid-detergent insoluble protein (ADIP) measurement which is associated with reduced forage digestion and protein utilization. Yu (1977) found that ADIP level was generally unaffected by heat treatments below 95°C but increased above 100°C. Yang et al. (1993) found that steam application at 110°C created unacceptably high levels of ADIP. In both these studies, hay was exposed to these temperatures for 0.25 to 120 h, much longer than the expected dwell time of steam application at the baler pick-up.

The objectives of this research were to determine how baling alfalfa hay in arid climates with a steam re-hydration system would affect dry matter losses while baling, bale density, and hay nutrient composition compared to baling with dew re-hydration; and to determine fuel and water use rates when baling with this system.

Figure 2. Steam re-hydration of alfalfa at baler pick-up.

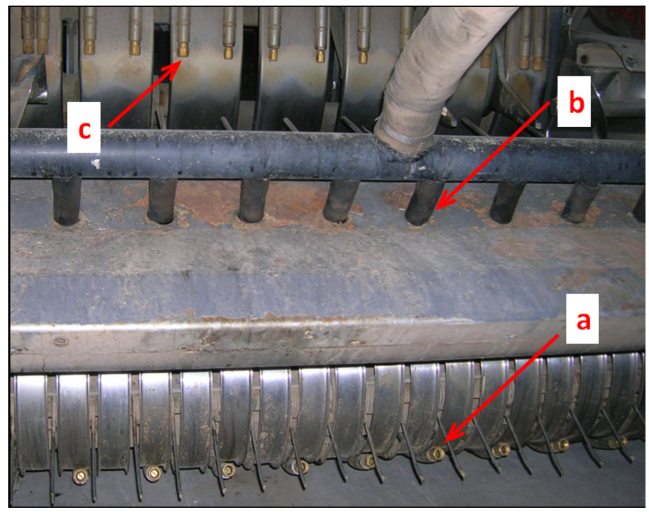

Figure 3. Three locations of steam nozzles at baler pick-up: (a) below pick-up at stripper bars; (b) above pick-up in wind guard; and (c) at entrance to pre-compression chamber.

Materials and Methods

The steam re-hydration system (fig. 1) consisted of a diesel-fueled boiler (45 kW), water feed pre-heater system (1,300 L), and water supply tanks (4,900 L). The boiler had industry standard safety control systems including a pressure regulator (100 kPa), flame safeguard and low-water cutoff (Staheli West, 2013). Low-pressure cone nozzles on 130 mm spacing were situated at the baler pick-up to apply steam to both the top and bottom of the incoming windrow (figs. 2 and 3). Steam rate was controlled by an electrically actuated steam modulation valve.

This research was conducted near Cedar City and Snowville, Utah where alfalfa grown under irrigation was cut with a 4.9 m sickle windrower and placed into a windrow slightly over 1.2 m wide. The alfalfa was allowed to dry for three days and then early in the morning when dew re-hydration was apparent, two windrows were merged into one with a single pass of a twin wheel rake. Field drying was

Figure 1. Steam generation unit located between the tractor and large square baler with steam applied at baler pick-up (Staheli West, 2013).

completed and baling then occurred on the fifth day after cutting.

Two experimental conditions were evaluated in all six tests (table 1): baling at night when dew re-hydration was apparent (dew) and baling in the day with steam re-hydration when the hay was generally less than 12% wet basis (w.b.) moisture (steam). Two additional treatments were used in the fifth test: baling during the day when no dew was apparent and the hay was generally less than 12% (w.b.) moisture (dry), and baling during the day when no dew was apparent and the hay was between 15% and 20% (w.b.) moisture (stem moisture). Only the dew, steam, and no re-hydration treatments were used for the final test. The advice of the two cooperating commercial hay producers was used to determine when the dew re-hydration level was sufficient and typical of their practices. Dew baling took place between midnight and 5:00 AM. Blocks were formed which consisted of two, three, or four windrows corresponding to the number of experimental conditions evaluated in that experiment. Windrows within a block were randomly assigned to each experimental condition. Baling commenced at the start of a windrow and continued through multiple blocks until the required number of replicate bales was produced (see below). Treatments baled during the day were baled between 10:00 AM and 6:00 PM.

The large square baler used was a Hesston model 4900 (Hesston, Kans.; 120 × 120 cm bale cross-section). Plunger load was maintained at about 70% of maximum which corresponded to a hydraulic pressure in the chamber convergence system of about 5,500 kPa. The baler was operated with a 120 kW tractor with typical baling speeds of 6.5 to 9.0 km/h. Ground speed was varied to produce 37 to 40 or 45 to 48 slices per bale when baling with dew or steam, respectively. More slices were placed in the bales formed with steam due to their greater density. The 3-tie baler used was a Hesston model 4690 (38 × 55 cm bale cross-section). Ground speed was varied to produce 14 to 16 or 16 to 18 slices per bale when baling with dew or steam, respectively.

Water and fuel use was quantified in separate tests by measuring the change in depth of the respective tanks during the time it took to form 24 large square bales. It was observed that steam application rate affected the chamber convergence pressure to maintain the desired plunger load, with greater steam rate producing a lower required convergence pressure. Therefore, as crop conditions varied throughout a test day, steam application rate was varied by throttling the steam flow to the nozzles to maintain the desired convergence pressure. The amount of steam actually applied to the hay was difficult to quantify because some steam dissipated to the atmosphere before it reached the crop. Also, some water vapor dissipated from the bale before it was bored for moisture determination, further complicating the estimate of the actual moisture applied to the hay. The average water use rate by the steam generation unit was about 44 L/ dry Mg hay (see results below).

Both balers were equipped with a plastic-covered frame that extended from the rear of the pick-up to just beyond of the end of the bale chute so that material falling from the pre-compression chamber, bale chamber, and bale chute was collected. For any experimental condition, the baler produced at least one large bale or five 3-tie bales before data collection began to ensure equilibrium conditions. When the knotter tripped to tie the final “equilibrium” bale, the baler was stopped and the loss frame cleaned. Baling then proceeded until one large bale or four 3-tie bales were formed. The baler was then stopped and the loss material on the frame was collected and placed in a plastic bag. Baling then proceeded until the full number of replicate bales was formed for that experimental condition.

Loss material was weighed to the nearest 50 g on a portable, platform scale of 45 kg capacity. Two representative sub-samples were collected and their moisture determined by oven drying at 103°C for 24 h (S358.2; *ASABE Standards*, 2012). The bales were weighed to the nearest 2 kg using a hanging scale of 2,300 kg capacity. Bale length was determined to the nearest 25 mm. The day after baling, bales were bored once from each end in the approximate bale center using a boring device of 50 mm diameter and 500 mm length. Both samples were blended together, separated into two paper bags, immediately weighed, and oven dried. A moisture sample was dried at 103°C for 24 h and a nutrient composition sample was dried at 55°C for 72 h (S358.2; *ASABE Standards*, 2012). Nutrient composition samples were analyzed for crude protein (CP), acid-detergent fiber (ADF), neutral-detergent fiber (NDF), and acid-detergent insoluble protein (ADIP) using near infra-red spectroscopy (NIR) techniques by the University of Wisconsin Soil and Plant Analysis Laboratory.

Table 1. Baling date, average ambient meteorological conditions during tests, baler type tested, and experimental conditions tested.

		Daytime Conditions[b]		Nighttime Conditions[c]			
Test	Date[a]	Temp. (°C)	Humidity (%)	Temp. (°C)	Humidity (%)	Baler[d]	Experimental Conditions[e]
1	22-Jun	27	11	12	37	LSB	ST, DW
2	23-Jun	27	14	15	43	LSB	ST, DW
3	28-Jun	31	27	8	84	LSB	ST, DW
4	30-Jun	35	23	12	64	LSB	ST, DW
5	1-Aug	30	12	12	45	3-tie	ST, DW, DR, SM
6	11-Aug	30	26	15	87	LSB	ST, DW, DR

[a] June dates were second cutting alfalfa; August dates were third cutting alfalfa.
[b] Ambient conditions from sling psychrometer measurements during time bales were formed using steam re-hydration or baled with no re-hydration.
[c] Ambient conditions from sling psychrometer measurements during time bales were formed using dew re-hydration.
[d] LSB – large square and 3-tie balers (120 × 120 cm or 38 × 55 cm bale cross-section, respectively).
[e] ST – daytime baling with steam re-hydration; DW – nighttime baling with dew re-hydration; DR – daytime baling using dry hay (<12% moisture); SM – daytime baling with stem moisture (15%-20% moisture).

Bale length, cross-section, and dry mass were used to calculate bale dry matter (DM) density. The dry mass of the bale and loss material were used to calculate DM loss, expressed as a percent of the total dry mass of the bale(s). Six replicate large square bales were formed for each experimental condition in the first four tests, with eight replicate bales formed in the sixth test. Twelve replicates consisting of four 3-tie bales were used per experimental condition in the fifth test. Only the steam and dew experimental conditions were considered in the first four tests, so the results of these tests were statistically analyzed together using a two-way analysis of variance in which the confounding effects of tests conducted on different days and fields were removed by blocking. The last two tests were each analyzed separately using one-way analysis of variance. For each analysis, an ANOVA using Microsoft Excel was performed and least-significant differences (LSD) between treatment means were calculated using a probability of 95%.

RESULTS

Losses were significantly less from bales formed with steam re-hydration even though these bales had lower moisture at baling (table 2). Losses for both treatments were quite low, but losses from large square balers are typically low (Shinners et al., 1996). Although not quantified, visual observation of the interior of the steam re-hydrated alfalfa bales indicated that leaf retention on the stems was superior to that of bales formed with dew re-hydration. Bale density was about 20% greater for those bales formed with steam re-hydration (table 2). It was observed that the addition of steam to the hay softened both the leaves and the stems, which made the stems more compliant and more easily flattened by the plunger. Stems in the bales formed with steam re-hydration were observed to have a flat cross-section while those formed with dew re-hydration were observed to have typical round cross-section.

Hay nutrient composition was not significantly different between the two treatments (table 2). The numerically greater CP and lower ADF and NDF levels for the steam re-hydration treatment were consistent with the greater retention of leaf tissue. The similar ADIP values between treatments indicate that the temperature increase due to the steam application was not of sufficient magnitude or duration to cause heat damage to plant protein.

Losses from steam re-hydrated 3-tie bales were 43%, 73%, and 71% less than losses for hay baled with dew, stem-moisture, or dry, respectively (table 3). Losses were greatest with the dry and stem-moisture treatments because the leaves were dry and brittle, as evident from the moisture of the loss material. The moisture of losses for the steam re-hydration treatment was about nine percentage units greater than the overall bale moisture. This was not the case with the large bales where loss moisture was about the same as bale moisture (tables 2 and 4). This difference in moisture could be attributed to two factors. First, flow rate from the steam generation system was similar when baling with either the large-square or 3-tie balers. However, the 3-tie baling capacity was less than the large baler, so steam application per unit mass of hay was greater for the 3-tie baler. Secondly, the time it took to produce four 3-tie bales was much less than that required forming one large bale, so the moisture applied as steam did not have as much time to dissipate before the loss material was collected and sampled.

Bale density of steam re-hydrated 3-tie bales was 29%, 37%, and 48% greater than those baled with dew, stem moisture or dry, respectively (table 3). These were larger increases than produced with the large square bales. This could be partially explained by the greater steam application rate per unit bale mass. Also, the time from steam application to impact by the plunger in the bale chamber was less for the 3-tie baler due to differences in plunger frequency between the baler types. The steam re-

Table 2. Hay moisture of bales and lost material; baler losses; bale density; and alfalfa hay nutrient composition for large-square bales formed during tests 1-4[a] (n = 24 bales per treatment).

Re-hydration Treatment	Moisture (% w.b.) Bales[b]	Moisture (% w.b.) Lost Material[c]	Losses from Baler (% of total DM)	Bale Density (kg DM/m^3)
Steam	8.6a	8.6a	0.5a	272b
Dew	11.2b	8.4a	1.2b	226a
LSD[c] (P = 0.05)	1.1	1.0	0.2	8
	Bale Nutrient Composition[d] (% of DM)			
	CP	ADF	NDF	ADIP
Steam	19.2a	29.1a	38.1a	0.70a
Dew	18.9a	29.4a	38.4a	0.72a
LSD[c] (P = 0.05)	0.5	0.9	1.0	0.02

[a] Weather conditions are found in table 1.
[b] Moisture content of hay in the bale and of material lost from the baler.
[c] Least significant difference; different letters in the same column are statistically different. Data analyzed using a two-way analysis of variance.
[d] CP – crude protein; ADF – acid detergent fiber; NDF – neutral detergent fiber; ADIP – acid-detergent insoluble protein.

Table 3. Hay moisture of bales and lost material; baler losses; bale density; and alfalfa hay nutrient composition for 3-tie bales formed during test 5[a] (n = 12 replicates per treatment with each replicate consisting of four 3-tie bales).

Re-hydration Treatment	Moisture (% w.b.) Bale[b]	Moisture (% w.b.) Lost Material[b]	Losses from Baler (% of total DM)	Bale Density (kg DM/m^3)
Steam	10.5b	19.3d	0.4a	282c
Dew	13.7c	14.3c	0.7b	218b
Stem-moisture	15.7d	10.3b	1.5c	206b
None	9.0a	9.2a	1.4c	190a
LSD[c] (P = 0.05)	0.4	0.5	0.1	11
	Bale Nutrient Composition[d] (% of DM)			
	CP	ADF	NDF	ADIP
Steam	20.5b	32.2b	41.6b	0.83a
Dew	20.8b	31.0a	40.7a	0.84a
Stem-moisture	20.5b	31.1a	41.2ab	0.83a
None	19.9a	32.0b	42.4b	0.83a
LSD[c] (P = 0.05)	0.5	0.8	0.8	0.01

[a] Weather conditions are found in table 1.
[b] Moisture content of hay in the bale and of material lost from the baler.
[c] Least significant difference; different letters in the same column are statistically different. Data analyzed using one-way analysis of variance.
[d] CP – crude protein; ADF – acid detergent fiber; NDF – neutral detergent fiber; ADIP – acid-detergent insoluble protein.

Table 4. Hay moisture of bales and lost material; baler losses; bale density; and alfalfa hay nutrient composition for large-square bales formed during test 6[a] (n = 8 bales per treatment).

Re-hydration Treatment	Moisture (% w.b.)		Losses from Baler (% of total DM)	Bale Density (kg DM/m³)
	Bale[b]	Lost Material[b]		
Steam	12.7b	12.2b	0.9a	224b
Dew	14.3c	14.3c	0.8a	224b
None	9.2a	8.1a	2.3b	210a
LSD[c] (P = 0.05)	0.8	0.4	0.2	5
	Bale Nutrient Composition[d] (% of DM)			
	CP	ADF	NDF	ADIP
Steam	21.2b	25.5b	39.6a	0.86a
Dew	20.4a	24.6a	39.4a	0.82a
None	20.5a	26.1c	40.8b	0.93b
LSD[c] (P = 0.05)	0.4	0.5	0.5	0.04

[a] Weather conditions are found in table 1.
[b] Least significant difference; different letters in the same column are statistically different. Data analyzed using one-way analysis of variance.
[c] Moisture content of hay in the bale and of material lost from the baler.
[d] CP – crude protein; ADF – acid detergent fiber; NDF – neutral detergent fiber; ADIP – acid-detergent insoluble protein.

hydration treatment had numerically lower CP and higher fiber (ADF, NDF) than the dew re-hydration treatment despite having significantly greater leaf tissue retention. No explanation could be found for this discrepancy, but differences in nutrient composition were quite small.

In the final test, large square bales baled with no re-hydration had significantly greater losses and lower bale density than the other two treatments (table 4). There were no significant differences between the steam or dew re-hydration treatments in terms of loss or density. This result was different than that found in the previous four tests with the large square baler and the difference may be attributed to two reasons. First, while baling with steam re-hydration, there was a malfunction in the bale chamber panel control system that produced an incorrect plunger load signal. This caused the operator to reduce steam application rate to unusually low levels to achieve the desired plunger load. Second, the crop was quite immature and was observed to have small, very fine stems. The phenomenon where the steam application softens the stem and allows it to be flattened by plunger loading might have been less evident with the fine, small diameter stems. Fiber content was greater for the dry baled treatment, consistent with the greater loss of leaf tissue (table 4). Differences in nutrient composition between the two re-hydration treatments were small with no evident pattern.

The quality of commercial hay sold in the western United States is based on both its nutrient composition (CP, ADF, NDF) and on its appearance (Putnam et al., 1997). Based on nutrient composition, alfalfa hay baled with the steam re-hydration system appeared to be equal to that of the dew re-hydration practice (tables 2-4). Based on the qualitative opinion of the cooperating commercial hay producers, the steam re-hydrated bales were judged to be dense, green in color and showed very good leaf attachment to the stem. This latter parameter is important to purchasers of commercial hay because leaves captured in the bale but removed from the stem are subject to loss during handling, mixing and feeding (Orloff and Mueller, 2008; Thomas, 2009). Dry hay baled during the daytime not only had greater losses, but the bales had an unacceptable appearance according to the qualitative opinion of the cooperating hay producers. Leaves and stem fragments were observed to easily slough off the bale edges, especially during handling. Although leaves were captured in these bales, when select bales were cut apart it was observed that a major portion of the leaves had been removed from the stem.

Diesel fuel use for the steam generation system varied between 1.7 and 5.2 L/Mg DM of hay baled but most measurements were between 3.2 and 4.2 L/Mg DM. Water use varied between 25 and 54 L/Mg DM but most often between 38 and 50 L/Mg DM. Using average values, the steam generation rate was 11.9 L of water per L diesel fuel consumed. This compares favorably with the boiler manufacturers maximum steam generation rate of 13.9 L water per L of fuel. If the initial hay moisture was assumed to be 9% (w.b.) and the typical baling rate was 30 Mg DM/h, then the application of water at the average rate would increase the bale moisture to about 14% (w.b.). Moisture of steam re-hydrated bales was typically much less than this (tables 2-4) because some steam escaped to the atmosphere before it could be applied to and absorbed by the hay. Improving the steam application efficiency would improve the economics of the process because a smaller steam generator could be used and less fuel consumed.

In all cases, the moisture of bales formed with steam re-hydration was below those formed with dew re-hydration (table 2-4). It is well known that excess moisture will cause spoilage in large, dense hay packages (Pitt, 1990; Shinners et al., 1996). Bales treated with steam application were taken apart several months after formation with no visible signs of degradation due to spoilage, suggesting that the added moisture from steam re-hydration did not reduce hay value.

Conclusions

Baling during the day under arid conditions with steam re-hydration increased leaf retention and reduced leaf loss compared to the typical practice of baling at night with dew re-hydration. When using the steam re-hydration process, bale chamber losses averaged 58% and 43% less for large-square (tests 1-4) and 3-tie balers, respectively, compared to baling with dew re-hydration. Steam re-hydration appeared to soften the plant almost immediately, allowing the baler plunger to flatten the stems, thereby increasing bale density. Compared to baling with dew re-hydration, steam re-hydration increased bale density by 20% and 30% for large-square (tests 1-4) and 3-tie bales, respectively. Steam re-hydrated hay had similar nutritional composition to dew re-hydrated hay. The increased temperature of the hay caused by steam application had no impact on heat-damaged protein (ADIP). Fuel use for steam generation typically varied between 3.2 and 4.2 L/Mg DM of hay produced and water use varied between 38 and 50 L/Mg DM. The average steam generation rate was 11.9 L of water per liter diesel fuel consumed. Steam re-hydration of alfalfa at the baler was a successful method of maintaining hay leaves and associated nutritive value when baling during the day in arid climates.

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