BIOLOGY AND EFFECTS OF SPONTANEOUS HEATING IN HAY

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ABSTRACT

The negative consequences of baling hay before it is adequately dried are widely known to producers. Frequently, these problems are created by uncooperative weather conditions that prevent forages from drying (rapidly) to concentrations of moisture that allow safe and stable storage of harvested forages. Negative consequences associated with baling hay before it is adequately dried include molding, spontaneous heating, undesirable changes in forage quality, and the potential for spontaneous combustion. The magnitude and duration of spontaneous heating is affected by numerous variables, including forage moisture content, bale size, bale density, climatic conditions, and use of preservatives. Most changes in nutritive value, including estimates of ruminal protein degradation and the associated ruminal decay rate, are related to spontaneous heating in surprising close linear relationships. Spontaneous heating has a profoundly negative overall effect on forage quality, and great care should be exercised to properly dehydrate forages prior to baling, thereby avoiding this undesirable phenomenon.

INTRODUCTION

Spontaneous heating is probably the most obvious result of plant and microbial respiration in which plant cells and different microorganisms consume sugars in the presence of oxygen to yield carbon dioxide, water, and heat:

plant sugars + oxygen ➔➔➔➔➔ carbon dioxide + water + heat.

This process causes the internal temperature of any hay bale to increase, thereby facilitating drying by encouraging evaporation of water, and ultimately lowering the energy content and digestibility of the forage. Numerous factors contribute to the extent of spontaneous heating; a partial list includes: i) moisture concentration at baling; ii) bale type; iii) bale density; iv) environmental factors, such as relative humidity, ambient temperature, and air movement; v) storage site; and vi) use of preservatives. Normally, the extent of heating that occurs in any hay bale is a good indicator of the undesirable changes in nutritive value that may be observed after storage.

PATTERNS AND CHARACTERISTICS OF SPONTANEOUS HEATING

Patterns of Heating. Figure 1 illustrates the typical patterns of spontaneous heating that occur over storage time for conventional rectangular bales of alfalfa hay made at 20 and 30% moisture.

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Beginning immediately after baling, the internal bale temperature increases as a result of respiration by both plant cells and microbes associated with the plant in the field (Roberts, 1995). This period of spontaneous heating often lasts less than five days. Following a short period in which internal bale temperatures may recede (at 4 to 5 days post-baling), a prolonged period of heating begins that can last for several weeks. This heating occurs primarily as a result of respiration by microorganisms that proliferate during bale storage. Furthermore, it should be noted that bales packaged at 30% moisture maintained a greater internal bale temperature than the drier hay for about 25 days. Similar trends can be observed for characteristics of spontaneous heating in conventional rectangular bales of bermudagrass hay (Figure 2), which is an important cash crop throughout much of the southeastern US. Tall fescue hay (39% moisture) packaged in large round bales (Figure 3) exhibited a similar chronological pattern, except that their was little evidence of a clear initial spike and heating persisted for approximately two months.

Moisture Content. Of all the factors that affect spontaneous heating, moisture content at the time of baling is the most important. Figure 4 summarizes several alfalfa hay experiments conducted in Kansas. A heating degree day (HDD) concept often has been used to integrate the magnitude and duration of heating in hay bales, and often it is used as a response variable in hay preservation studies. The positive linear relationship between moisture content and HDD is remarkably close ($r^2 = 0.902$) for a biological system. All bales within this summary were packaged within conventional rectangular bales, and the summary includes studies conducted at different times with bales of different densities, including some that were mismanaged intentionally to create a negative response. This establishes clearly that moisture content is the primary variable driving spontaneous heating within any given bale type. While it is generally assumed that similar relationships between moisture content and spontaneous heating exist in large round or other large bale types, documented research supporting this is limited. Because bale size and density also affect spontaneous heating, the close linear relationship between spontaneous heating and moisture content observed in Figure 4 would likely deteriorate if data from different bale types were used within the same linear regression.

Bale Size and Density. Both size and density of bales have a positive effect on spontaneous heating in hay packages. Density enhances spontaneous heating simply by packing more DM into the bale, but not by causing any change in the heat produced per unit of forage DM (Nelson, 1966; Rotz and Muck, 1994). However, a mean density difference of 1.4 lbs/ft^3 for bales packaged at five moisture concentrations ranging from 18 to 33% did not result in detectable differences in heating characteristics within conventional rectangular bales of bermudagrass hay (Coblentz et al., 2000). Larger and denser packages also tend to have higher internal bale temperatures because the heat produced is more difficult to dissipate. This was illustrated by Montgomery et al. (1986) who reported that mixtures of orchardgrass and alfalfa packaged at 23.0% moisture in 1375-lbs large round bales reached a peak internal bale temperature of about 190°F compared to only 104°F for 25-bale stacks of conventional rectangular bales made from the same forage. However, the maximum internal bale temperatures for both of these bale types occurred at about the same time chronologically (after 11 to 12 days of storage). This chronological similarity was observed generally for heating characteristics within 4 x 3½-foot round bales of tall fescue hay baled at 39% moisture (Figure 3) and in Figures 1 and 2 for alfalfa and bermudagrass hays, respectively, packaged in conventional rectangular bales. These tall fescue hay bales were relatively small (783 lbs) compared to other large hay packages, and they would be expected to heat less severely than larger bales of the same forage. Typically, the recommended moisture content at baling for larger, round hay bales is lower than is necessary for conventional rectangular bales. A good rule of thumb for maintaining acceptable storage in conventional rectangular hay packages is to bale hay at 20% moisture or less; however, this guideline is often reduced to 16% moisture or less for large-round or other large hay packages.

Combustion. Festenstein (1971) has suggested that internal bale temperatures in excess of 158ºF are likely generated by oxidative reactions, rather than by microbial and plant respiration, largely because enzymes can be denatured and their systems rendered inactive at high temperatures. High (> 158ºF) temperatures caused by oxidative chemical reactions may occur more than 30 days after baling. Clearly, large round bales are more prone to heat spontaneously and have a higher risk of spontaneous combustion, particularly when internal bale temperatures reach about 340ºF (Collins, 1995). Normally, this does not occur in the center of the stack because lower concentrations of oxygen may limit temperature increases and make combustion less likely. It is more commonplace for spontaneous combustion to occur near the outside of the stack where more oxygen is available.

DRY MATTER LOSSES IN HEATED HAYS

Dry matter (DM) is lost whenever heating occurs in hay bales. These losses occur in virtually all hays, but are relatively minor in conventional rectangular bales packaged at about 15% moisture that exhibit no evidence of spontaneous heating. Given the lack of precision and accuracy inherent in making these types of measurements within a field-scale context, these DM losses may not be detectable. Much of the DM that is lost during hay storage is nonstructural carbohydrate (mostly sugars) that are respired to carbon dioxide, water, and heat, and these losses increase with moisture content at baling and subsequent spontaneous heating. Figure 5 summarizes DM recoveries from conventional rectangular alfalfa and bermudagrass hay bales obtained from several experiments conducted in Kansas and Arkansas, respectively. For conventional rectangular bales of alfalfa, losses of DM can exceed 10% when the moisture concentration at baling approaches 30% (Figure 5). Although direct experimental comparisons are not available, circumstantial evidence suggests that DM losses for alfalfa are greater than those observed for warm-season perennial grasses, such as bermudagrass, when compared over similar ranges of heating. This may be related to the higher concentrations of nonstructural carbohydrates in alfalfa compared to those found in many perennial warm-season grasses. Although it is assumed that these overall trends are similar for larger hay packages, DM recoveries should be poorer in larger packages made at comparable concentrations of moisture due to the greater susceptibility for spontaneous heating within these larger bale types.

NUTRITIONAL CHARACTERISTICS OF HEATED HAYS

Nonstructural Carbohydrate (TNC). As a standing crop, the concentrations of nonstructural carbohydrates in alfalfa can exceed 20% of the total plant DM, normally reaching maximum in the late afternoon or early evening (Holt and Hilst, 1969; Lechtenberg et al., 1971). During daylight hours, photosynthate accumulates because energy from sunlight is converted into sugars at a faster rate than it can be oxidized to meet the immediate energy needs of forage plants and/or stored for later use. Even when alfalfa is wilted under excellent drying conditions, the concentrations of nonstructural carbohydrates can fall to < 8% of DM by the time the forage is baled. This occurs as a result of unavoidable plant respiration during the wilting process. Despite the losses of TNC that occur during wilting, hay cut at sundown and dried under good wilting conditions should have higher concentrations of TNC than hay cut at sunup; Fisher et al. (2002) reported this difference in concentration to be about 1.0 percentage unit when averaged over three harvests at midbud stage for alfalfa grown in Idaho. In several studies, these relatively small differences in concentrations of sugars can have a positive effect on animal preference and the subsequent intake of DM by livestock.

During storage, concentrations of TNC decline in a curvilinear pattern with storage time (Table 1; Coblentz et al., 1997a), but final concentrations are highly dependent upon storage conditions. Recovery of TNC will be greater in nonheated hays than in heated hays, and concentrations of TNC have been related to spontaneous heating in negative, linear relationships (Coblentz et al., 1997a). The time interval when concentrations of TNC fall most rapidly (0 to 12 days) coincides with the onset of the most intense heating in hay bales (see Figures 1-3). During this initial period of intense spontaneous heating, plant sugars in all hays are oxidized as a fuel source for rapidly proliferating microorganisms in the hay.

Table 1. Concentrations of total nonstructural carbohydrates (TNC) in alfalfa hays packaged in conventional rectangular bales at 20 and 30% moisture and sampled over time in storage (adapted from Coblentz et al., 1997a).

	-------- Moisture content of hay at baling --------	
Storage time	30%	20%
days	------------------------- % TNC ------------------------	
0	5.96	7.29
4	5.63	5.17
11	3.67	3.95
22	2.71	3.59
60	2.07	4.21

Fiber Components. Forage fiber components, such as NDF, ADF, crude fiber, lignin, and ash, remain relatively stable during bale storage. These components comprise the cell wall or structural portion of forages, and they are the least digestible parts of the plant. Generally, DM loss as a consequence of spontaneous heating is associated with respiration of TNC; therefore, concentrations of fiber components increase primarily by indirect mechanisms, and not as a result of synthesizing additional plant fiber. Concentrations of fiber components typically increase linearly (Figure 6) with measures of spontaneous heating, such as maximum temperature, average temperature, or HDD, and the r^2 statistics for these linear regressions are generally quite high (> 0.7) for both bermudagrass (Coblentz et al., 2000; Turner et al., 2002) and alfalfa (Coblentz et al., 1996). In addition, Turner et al. (2002) found that changes in concentrations of fiber components (NDF, ADF, and lignin) for heated bermudagrass hays are closely related to time in storage; generally, rapid changes occur during the first 12 days of storage, but concentrations generally stabilize thereafter.

Total Digestible Nutrients (TDN). Measures of the energy content within a forage, such as TDN or net energy, are often predicted from equations based largely on concentrations of fiber components (ADF and/or NDF). Any process, such as spontaneous heating, that increases the concentrations of fiber components within in a forage likely will have a negative effect on estimates of energy.

Digestibility. The digestibility of forages is reduced in response to spontaneous heating, largely due to the oxidation of TNC, which is highly digestible, and the increased concentrations of fiber components, which are digested incompletely. For bermudagrass hay made in Fayetteville in 1998, the effects of heating on forage digestibility (measured as IVDMD) appeared to be minimal when the internal bale temperature did not exceed 120°F. However, digestibility decreased by about 14 percentage units when the maximum internal bale temperature exceeded 140°F. Similarly, McBeth et al. (2001) reported that digestibility coefficients for DM, organic matter (OM), NDF, and hemicellulose measured in lambs consuming heated bermudagrass hays declined linearly with HDD accumulated during bale storage (Table 2), but voluntary intake was not generally affected.

Table 2. Digestibility coefficients for DM, OM, NDF, ADF, and hemicellulose measured in lambs offered common bermudagrass hays subjected to various levels of spontaneous heating (adapted from McBeth et al., 2001).

	---------- HDD[a] ----------				
Item	5	119	201	273	401
	---------- % ----------				
DM[b]	58.3	59.4	56.6	51.0	54.4
OM[b]	58.6	59.5	56.5	51.1	54.0
NDF[b]	65.6	66.5	65.4	60.4	62.5
ADF	55.9	58.1	56.2	52.0	54.8
Hemicellulose[b]	73.2	73.4	73.8	68.1	68.9

[a] Calculated as the summation of the daily increments by which bale temperature was > 95°F during 60 days of storage.
[b] Slope of digestibility coefficient on HDD differed from zero ($P \leq 0.02$).

Crude Protein (CP). Generally, the changes in concentrations of CP are somewhat dependent on time since baling. In the short term (< 60 days), concentrations of CP may actually increase (Rotz and Abrams, 1988; Coblentz et al., 2000) because of preferential oxidation of TNC. Table 3 illustrates the effects of spontaneous heating on CP in bermudagrass hay bales that were sampled after 60 days in storage. For conventional rectangular bales of bermudagrass, these increases are linear functions of both moisture concentration at baling and measures of spontaneous heating (Coblentz et al., 2000; Turner et al., 2002). The long-term effect of spontaneous heating during bale storage is to decrease CP content. Crude protein can be reduced by 0.25 percentage units per month of long-term storage due to volatilization of ammonia and other nitrogenous compounds (Rotz and Muck, 1994); however, this loss is unlikely to continue indefinitely.

Heat-Damaged Protein. Maillard or nonenzymatic browning reactions occur in hays as a consequence of spontaneous heating, and these reactions may impact the apparent digestibility of N more severely than the concurrent impact of heating on the digestibility of fiber components. In Maillard reactions, carbohydrates are degraded in the presence of amines or amino acids to yield polymers that are largely indigestible in ruminants. Normally, heat-damaged protein is determined by quantifying the N remaining in forage residues after digestion in acid detergent (ADIN). Unlike fiber components, concentrations of ADIN increase primarily by direct mechanisms. Moisture content, the magnitude and duration of spontaneous heating, and forage type all affect the amount of heat damage that may occur to forage proteins. Moisture plays a critical role in this process in two distinct ways. First, it has a catalytic effect, which is why silages are more susceptible to heat damage than forages conserved as hay. Secondly, the moisture within the hay at baling stimulates spontaneous heating, which subsequently increases the probability of heat damage.

Table 3. Concentrations of CP for bermudagrass hay bales made from the same field and sampled after 60 days of storage at Fayetteville, AR, during 1998 (adapted from Coblentz et al., 2000).

Initial moisture Content	HDD[a]	Maximum temperature	CP
%		°F	%
33.6	1057	142	15.7
31.3	1055	144	15.3
29.8	990	138	15.0
27.7	1100	140	15.0
26.6	925	135	15.8
22.9	763	124	14.2
21.1	621	111	14.0
20.5	542	109	15.4
18.7	484	108	14.5
16.9	445	101	14.2

[a] HDD = heating degree days > 86°F.

Figure 7 illustrates the positive linear relationship between ADIN and spontaneous heating that exists for both alfalfa and bermudagrass hays. All forages have some indigestible protein that is inherently unavailable to livestock, but this fraction is generally small in most standing forages or unheated hays. Concentrations of ADIN in unheated alfalfa can range between 3 and 6% of total N. Typically, the indigestible protein in unheated warm-season grasses represents a higher percentage of the total forage N, and it can exceed 20% of total N in dormant forages. Grass hays are typically more susceptible to heat damage than alfalfa or other legumes. For example, bermudagrass exhibited greater increases of ADIN per unit of heating (Figure 7) than alfalfa; for bermudagrass, this may be related to high concentrations of hemicellulose, which is a reactive fiber component and structural carbohydrate. Ruminant nutritionists usually consider alfalfa hay to be seriously heat damaged when concentrations of ADIN exceed 10% of total N. Other management factors, such as using large and/or high-density hay packages, will increase the possibility of spontaneous heating and the probability of heat damage to forage proteins. Even though concentrations of ADIN increase by mechanisms different than those for fiber components, most increases for ADIN still occur early in the storage period (< 20 days).

Theoretically, ADIN is unavailable to ruminants; however, there is evidence that this is primarily a characteristic of native, or naturally occurring ADIN. Recently, McBeth et al. (2001) reported that digestibility coefficients measured in lambs for neutral detergent insoluble N (NDIN) decreased, but coefficients for ADIN increased linearly with spontaneous heating in bermudagrass hays (Table 4). Similarly, Broderick et al. (1993) reported a digestibility coefficient of -12.2% for ADIN in an unheated (ADIN = 4.4% of total N) alfalfa hay diet, but the digestibility increased to 35.8% when the diet contained steam-treated alfalfa hay with ADIN accounting for 16.3% of the total N in the forage.

Table 4. Digestibility coefficients for neutral detergent insoluble N (NDIN) and ADIN in heated bermudagrass hays (adapted from McBeth et al., 2001).

	HDD[a]				
Item	5	119	201	273	401
	%				
NDIN[b]	85.3	84.6	80.6	75.4	77.0
ADIN[b]	-1.7	16.5	29.6	21.7	42.3

[a] Calculated as the summation of the daily increments by which bale temperature was > 95°F during 60 days of storage.
[b] Slope of digestibility coefficient on HDD differed from zero ($P \leq 0.01$).

Ruminal Protein Degradability. Considerable research effort has been devoted to assessing the characteristics of ruminal degradability for forage proteins. Much of this research effort has been centered around efforts to improve dairy production. High-quality forages, such as alfalfa, frequently have high concentrations of CP, but this protein is degraded rapidly in the rumen, and therefore, can be utilized inefficiently by dairy cows and other livestock. Spontaneous heating limits both the rate (Figure 8) and amount of alfalfa forage protein degraded in the rumen. The spontaneous heating incurred in alfalfa hay baled at 30% moisture reduced the ruminal degradation rate by about 40% in a linear relationship with HDD (Figure 8; Coblentz et al., 1997b). While this may provide some benefit with respect to nitrogen retention and utilization, it should not be viewed as a justification for allowing forages to heat intentionally in the bale. Ruminal degradability of proteins from warm-season grasses, such as bermudagrass, is naturally less rapid. This natural resistance to ruminal degradation can be explained on the basis of differences in plant anatomy associated with the C3 and C4 photosynthetic pathways. Unlike alfalfa and other legumes, it is not necessarily desirable to slow the rate of ruminal degradation for proteins found in warm-season forages. Estimates of rumen degradability have been reduced linearly by spontaneous heating for both alfalfa and bermudagrass hays. Decreases of 0.15 percentage units of total CP per degree of maximum internal bale temperature were observed over harvests from two years for bermudagrass hays (Figure 9; Coblentz et al., 2001). Similarly, a negative slope of 0.018 percentage units of total CP per HDD > 30ºC (r^2 = 0.684) also was observed for alfalfa (Coblentz et al., 1997b) using the in situ method of evaluation. Protein bypassing the rumen has been assumed to be 80% digestible (NRC, 1996), but this clearly may vary with source and processing/handling conditions, and other sources (NRC, 2001) have assigned variable digestibilities rumen bypass protein. Within the narrow context of protein degradation for alfalfa hay, there may be some limited benefit to a very modest amount of spontaneous heating; however, heating can not really be controlled, and the negative consequences of inadequate dessication prior to baling, such as mold development, increased concentrations of fiber components, reduced energy density, and reduced total and component digestibilities, are enormous compared to any possible benefit by slowing ruminal protein degradation.

SUMMARY

Spontaneous heating occurs as a result of the plant or microbial respiration of plant sugars to carbon dioxide, water, and heat. Within any given bale type, moisture content at baling is the primary variable determining the magnitude and duration of heating. Concomitant with spontaneous heating are losses of DM from the bale; these losses, which are mainly in the form of sugars or other nonstructural carbohydrate, often exhibit a positive linear relationship with measures of heating. Most fiber components are relatively inert during the spontaneous heating process, but their concentrations increase linearly with measures of spontaneous heating because sugars and other compounds are oxidized preferentially. These processes will likely reduce both digestibility and the energy density of the forage. Similarly, concentrations of CP may increase during short-term storage, but volatilization of ammonia and other N compounds may occur over extended storage periods. Unlike fiber components, ADIN largely increases via direct mechanisms with spontaneous heating. Normally, the relationship between artifact N and heating is both positive and linear over a wide range of heating. Estimates of ruminal protein degradability and the associated ruminal decay rate are both limited by spontaneous heating, but it should be emphasized that these responses should not be viewed as a justification for allowing spontaneous heating to occur.

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Figure 1. Internal bale temperature versus storage time curves for conventional rectangular bales of alfalfa hay packaged at 20 and 30% moisture (adapted from Coblentz et al., 1996).

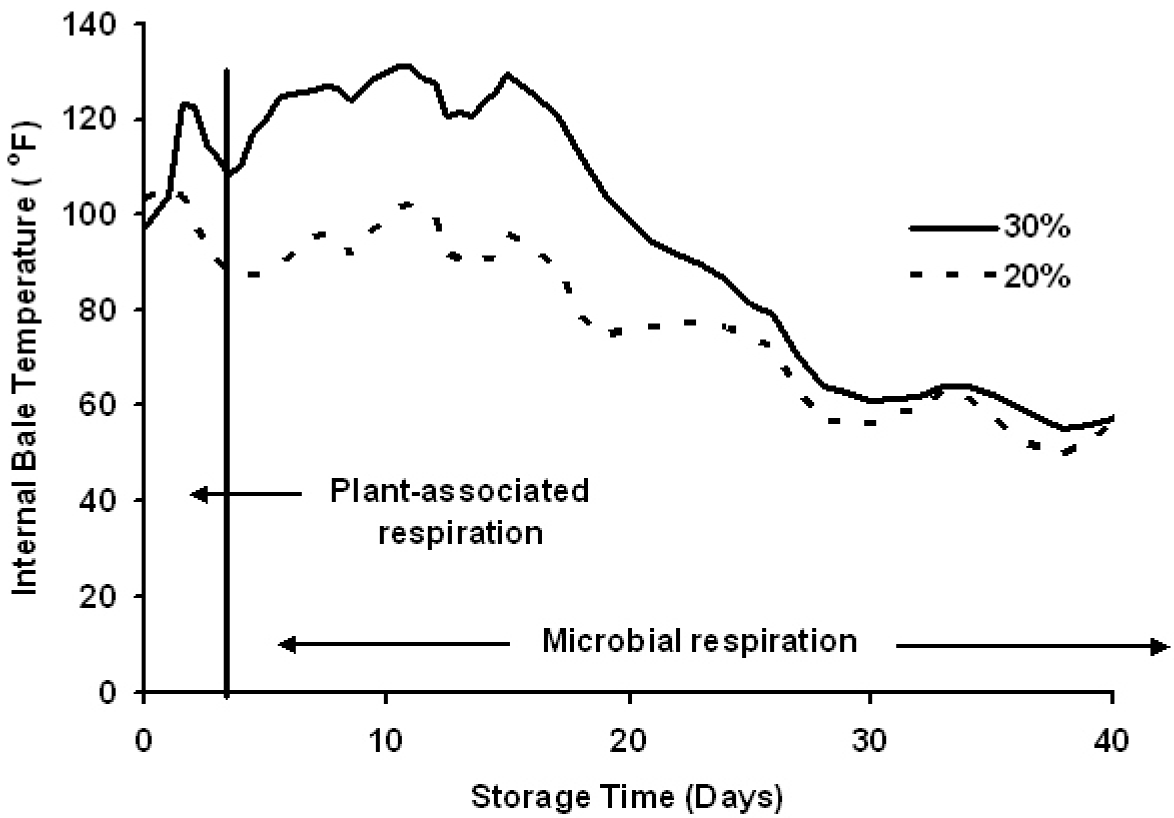

Figure 2. Internal bale temperature versus time curves for conventional rectangular bales of bermudagrass hay packaged at 17, 27, and 31% moisture (adapted from Coblentz et al., 2000).

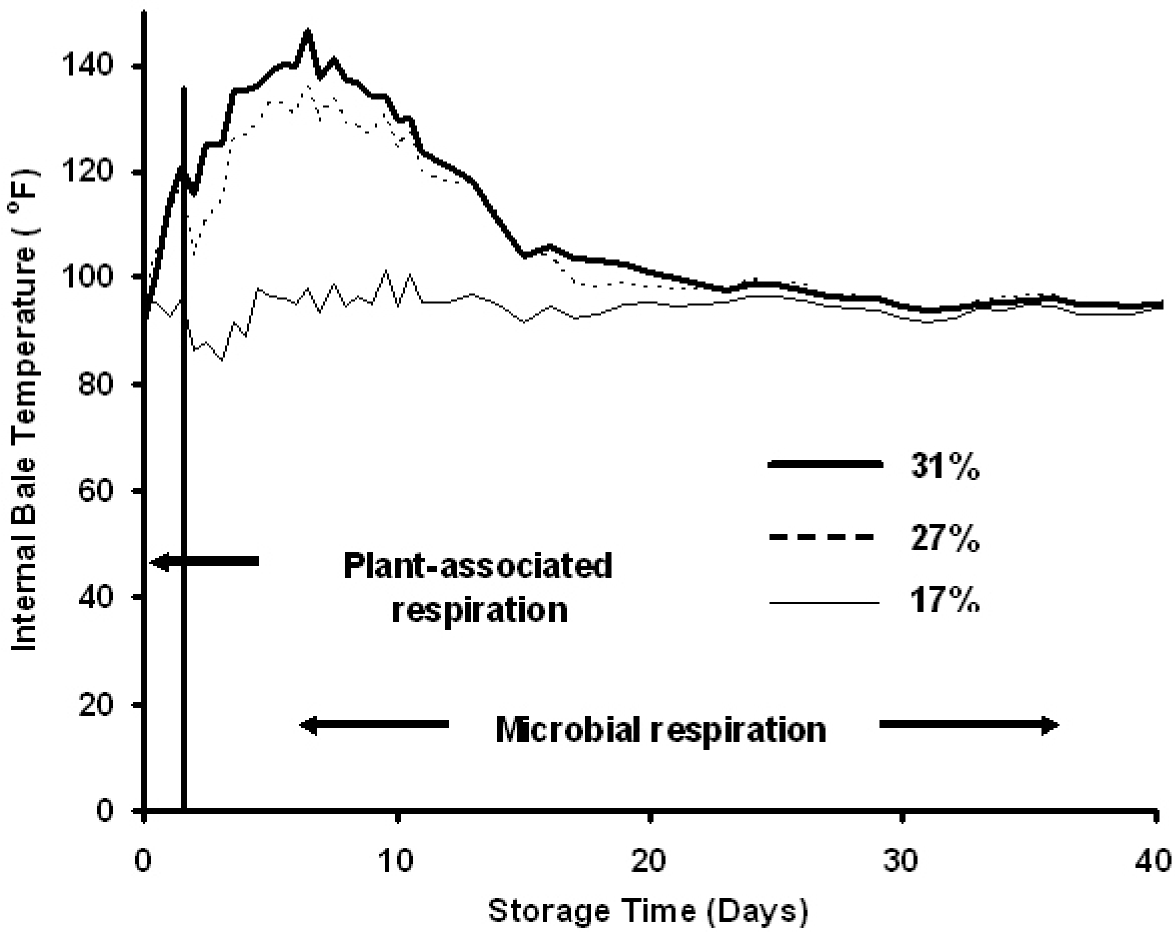

Figure 3. Surface (thin line) and core (heavy line) temperatures for large round bales of tall fescue made at 39% moisture at Fayetteville, AR. Bales were 4 x 3½ feet, and the mean initial bale weight was 783 lbs.

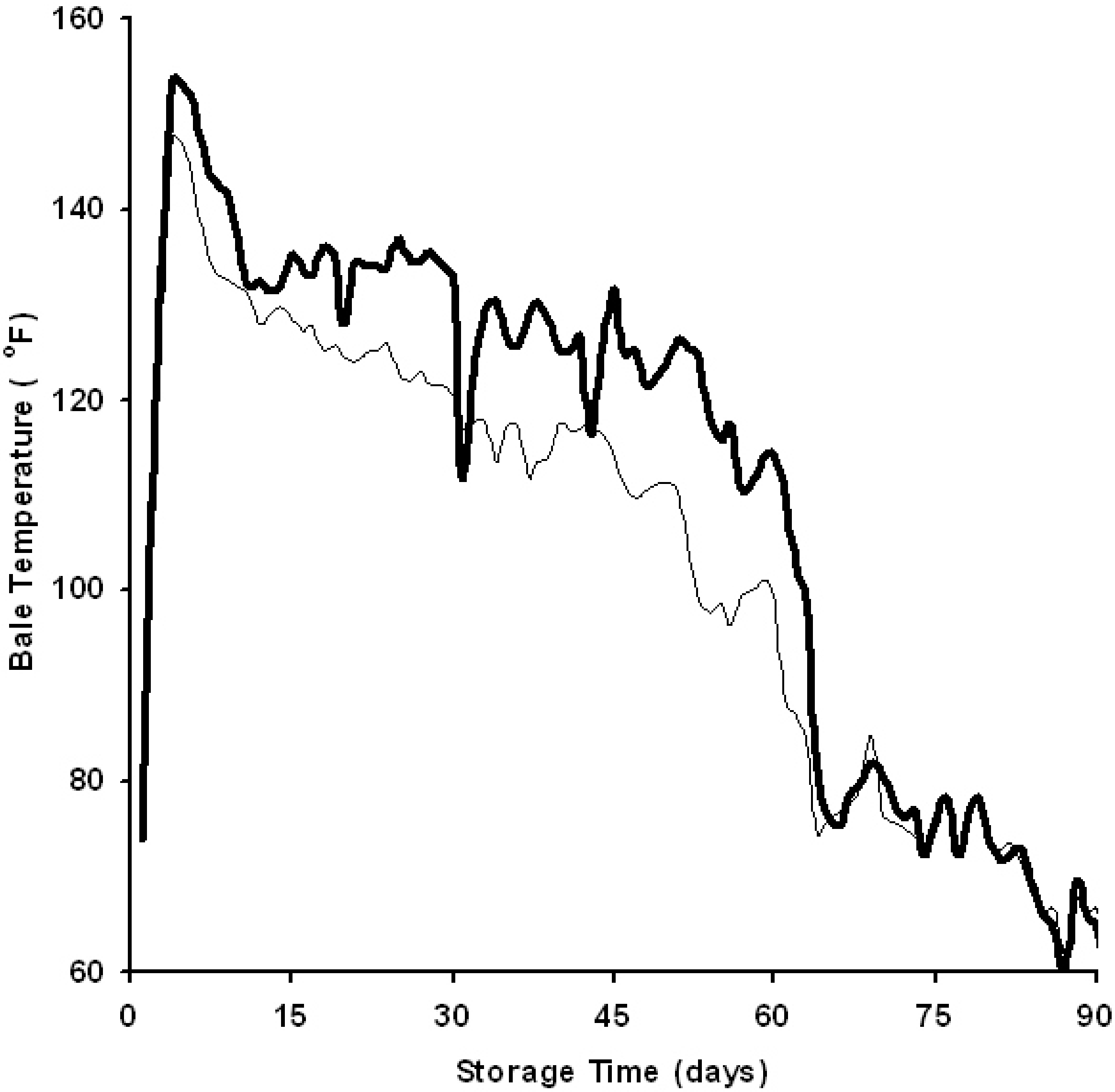

Figure 4. Relationship between heating degree days > 86ºF (a numerical index that integrates the magnitude and duration of heating) and moisture content at baling.

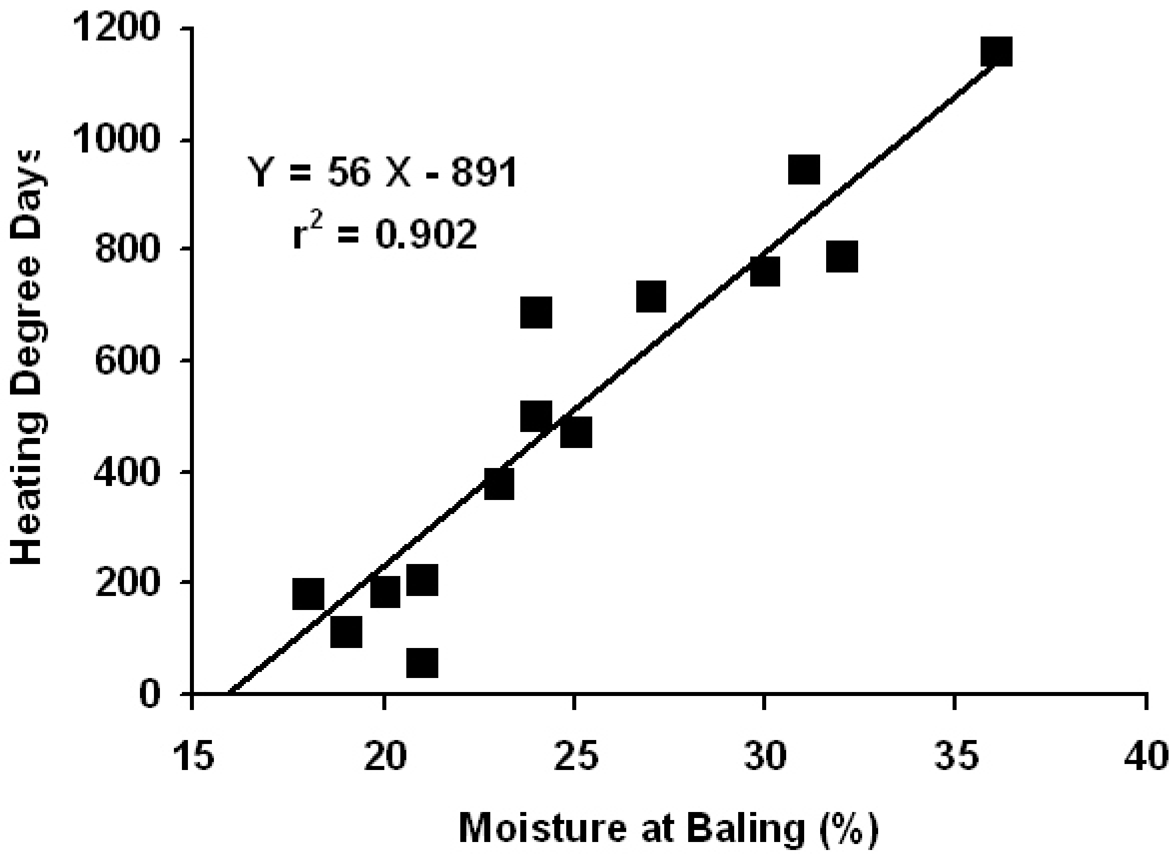

Figure 5. Dry matter recovery from small conventional bales of alfalfa and bermudagrass hays made in Kansas and Arkansas, respectively, as affected by spontaneous heating measured as heating degree days > 86ºF.

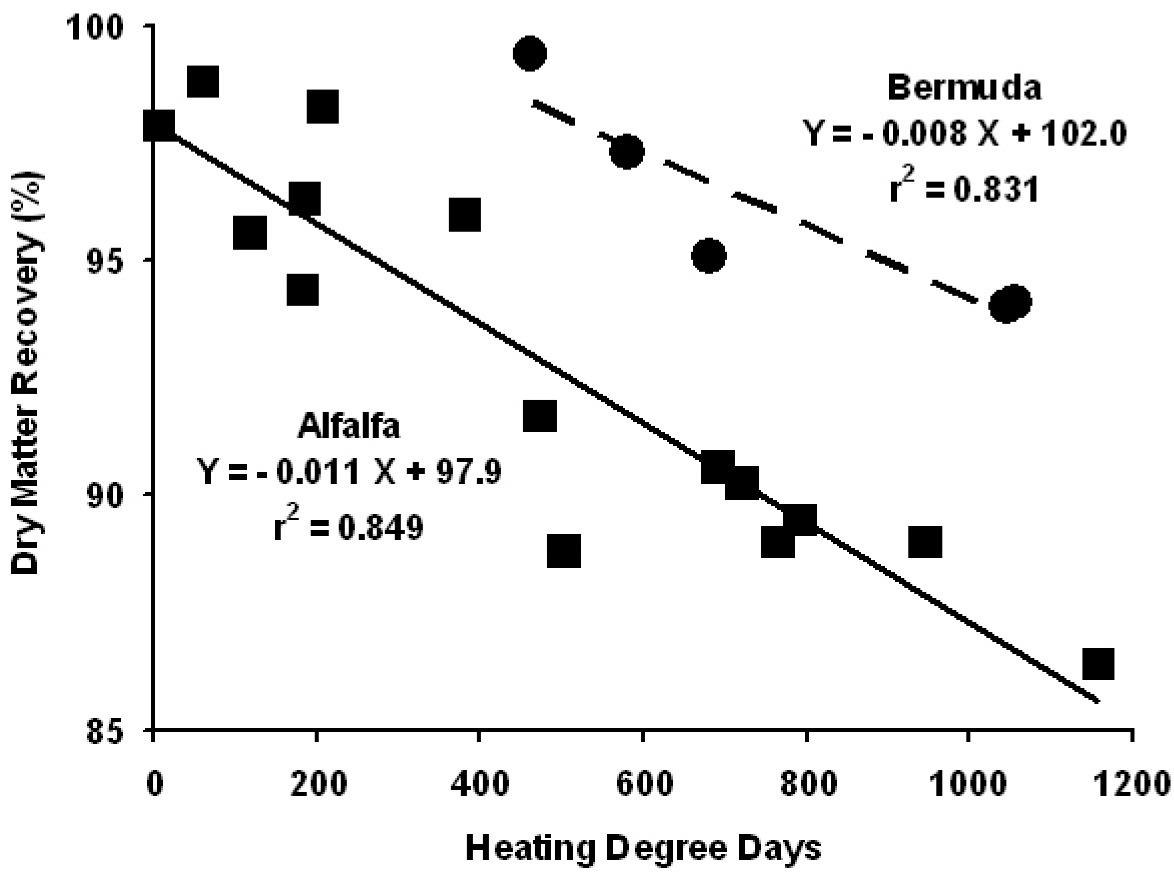

Figure 6. Relationship between NDF and maximum internal bale temperature for conventional rectangular bales of bermudagrass hay packaged in Fayetteville, AR in 1998 (adapted from Coblentz et al., 2000).

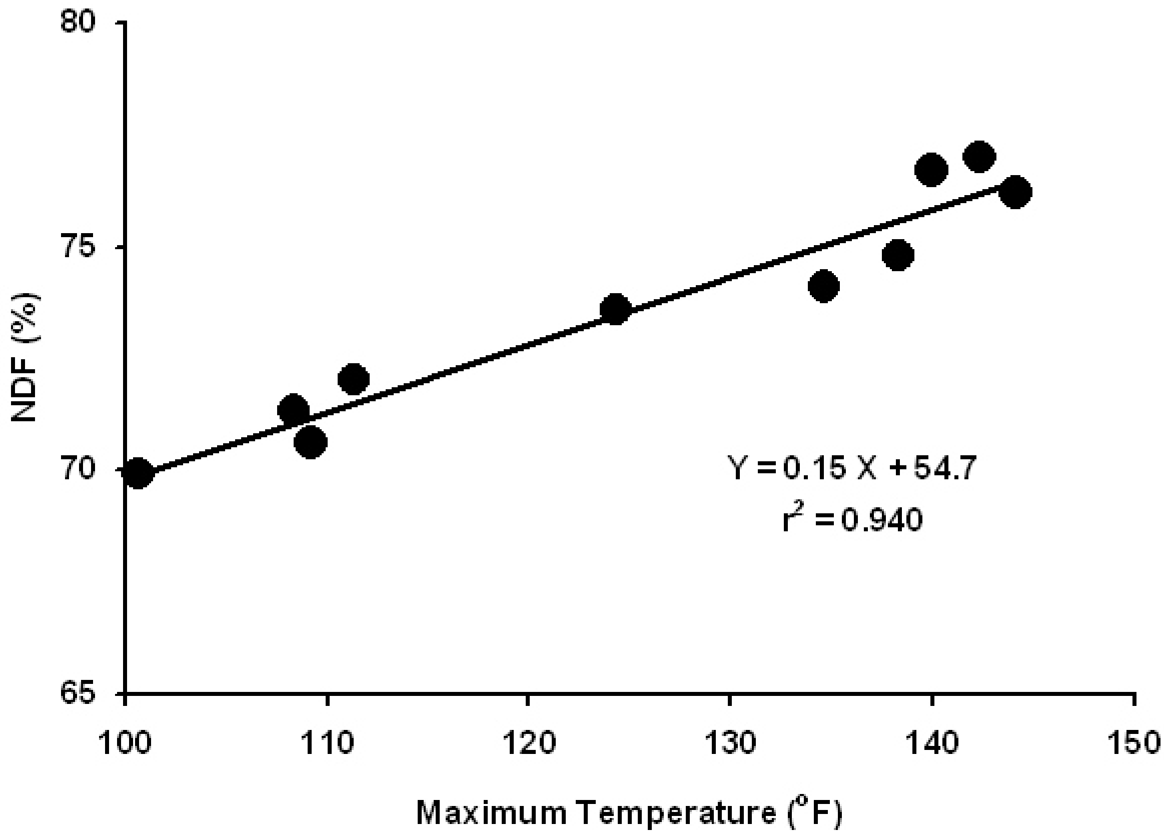

Figure 7. Relationship between ADIN and HDD for alfalfa (■) and bermudagrass (●) hays packaged in conventional rectangular bales in Manhattan, KS (1991) and Fayetteville, AR (1998), respectively.

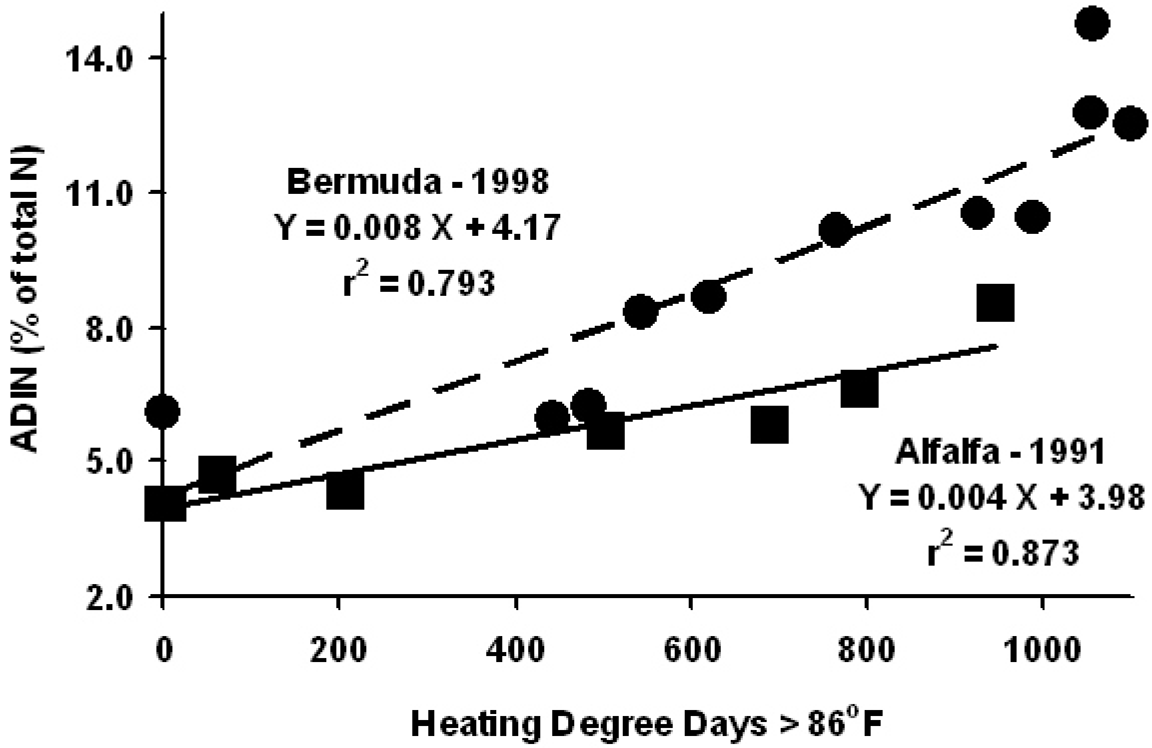

Figure 8. Effect of spontaneous heating on the ruminal protein degradation rate for alfalfa hay baled at 30% moisture and sampled over time in storage in Manhattan, KS (adapted from Coblentz et al., 1997b).

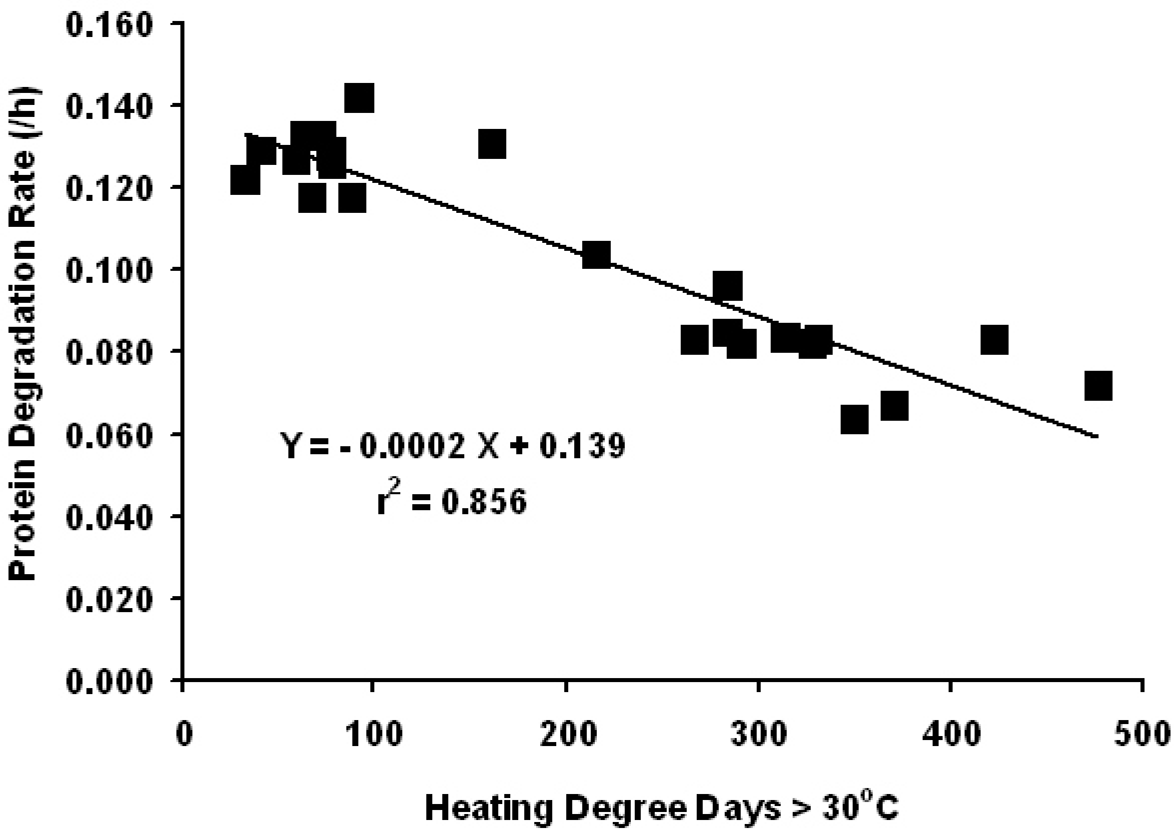

Figure 9. Relationship between estimates of ruminal protein degradability for bermudagrass hays harvested in 1998 (◆) and 1999 (◇) in Fayetteville, AR (adapted from Coblentz et al., 2001).