Storage characteristics, nutritive value, and fermentation characteristics of alfalfa packaged in large-round bales and wrapped in stretch film after extended time delays¹

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ABSTRACT

The production of baled silage is attractive to producers because it offers advantages over dry hay, particularly by limiting risks associated with wet or unstable weather conditions. Our objectives were to test the effects of delayed wrapping on silage fermentation, storage characteristics, and the nutritive value of baled alfalfa silages. To accomplish this, large-round bales of alfalfa were wrapped in plastic film within 4 h of baling (d 0), or after delays of 1, 2, or 3 d. A secondary objective was to evaluate a prototype bale wrap containing an O₂-limiting barrier (OB) against an identical polyethylene wrap without the O₂ barrier (SUN). Sixty-four 1.19 × 1.25-m bales of alfalfa were made from 4 field blocks at a mean moisture concentration of 59.1 ± 4.3% with a mean initial wet bale weight of 473 ± 26.4 kg. Two bales per field block were assigned to each combination of bale wrap (SUN or OB) and wrapping time (0, 1, 2, or 3 d postbaling), and one bale of each pair was fitted with a thermocouple placed in the geometric center of each bale. All bales were sampled after a 97-d storage period. Internal bale temperatures, recorded at the time bales were wrapped, were greater for all bales with wrapping delays compared with bales wrapped on d 0 (54.9 vs. 34.9°C), and increased to a maximum of 63.9°C after a 3-d delay exhibiting a linear effect of time delay. Total silage fermentation acids (lactic, acetic, propionic, butyric, and isobutyric) were greatest when bales were wrapped on d 0 compared with all bales wrapped with time delays (4.64 vs. 2.26% of DM), and declined with linear and quadratic effects of wrapping delay. Total fermentation acids also were related

quadratically to internal bale temperature by regression [y (% of DM) = 0.0042x² – 0.50x + 17.1; R² = 0.725]. Similar responses were observed for lactic acid, except that trends were linear, both for orthogonal contrasts evaluating length of wrapping delay, and in regressions on internal bale temperature [y (% of DM) = –0.046x + 3.5; R² = 0.663]. Butyric acid also was detected, regardless of treatment, but was greatest within bales wrapped on d 0 compared with those with wrapping delays (0.99 vs. 0.38% of DM), and a similar response (0.68 vs. 0.52% of DM) was observed for NH₃-N, suggesting that clostridial activity occurred during silage fermentation. Based on these results, silage fermentation characteristics and the nutritive value declined with time delays before wrapping, but responses were exacerbated when delays exceeded 1 d.

Key words: alfalfa, baled silage, oxygen barrier, wrapping delay

INTRODUCTION

The production of baled silage is attractive to many small or mid-sized dairy producers because it offers several advantages over conserving forages as dry hay. Perhaps the most important advantage is the reduced risk of rain damage to forage crops because the time requirement for wilting to a recommended moisture threshold for this silage type (~45 to 55%; Shinnars, 2003) is greatly reduced relative to the time required to wilt forages properly for conservation as dry hay. Other advantages over dry hay include (1) better retention of leaves from legume forages, and (2) potential for outside storage because the ensiled forage is wrapped completely in film, and therefore sheds water. However, silage fermentation within wrapped round-bales differs somewhat from precision-chopped silages. Typical moisture recommendations for baled silages range from 45 to 55% (Shinnars, 2003), which is considerably drier than recommendations for precision-chopped alfalfa silages (≤70%; Muck et al., 2003). This lower moisture

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may restrict the production of fermentation acids and limit the concomitant pH depression within the silage (Nicholson et al., 1991). Furthermore, the long-stem nature of baled forages restricts the release of sugars required for fermentation by lactic-acid-producing bacteria (Nicholson et al., 1991; Muck et al., 2003; Savoie and Jofriet, 2003), slowing the rate and limiting the extent of silage fermentation. This problem also may be exacerbated by the forage DM densities produced by round balers, which often are less than well-packed, precision-chopped silages.

Other factors also may affect the fermentation characteristics of round-bale silages. One such factor is the potential for delays in wrapping silages after baling is completed, which allows O₂ access to the silage mass, and can cause increased internal bale temperatures, oxidation of water-soluble carbohydrates, a greater final silage pH, and if wrapping delays are extended, formation of N-containing Maillard products that have poorer bioavailability within livestock than native forage N compounds or proteins (McBeth et al., 2001). Moshtaghi Nia and Wittenburg (2000) observed most of these responses following a 19-h wrapping delay when whole-crop barley silage was wrapped within 2, 10, or 19 h of baling; however, differences between 2- and 10-h delays generally were minimal. Borreani and Tabacco (2008) have raised more subtle issues related to O₂ infiltration based on the greater ratio of surface area to total silage DM in silage bales compared with chopped silages stored in bunkers or other large silo structures, as well as the somewhat permeable nature of bale wraps to O₂, particularly when an inadequate number of polyethylene film layers are applied. Hancock and Collins (2006) evaluated the effect of polyethylene layers on preservation of alfalfa baled silage, determining that 2 wrapping layers was inadequate for preservation, but little advantage was gained by using more than 4 film layers within a 5-mo storage period in Kentucky. Permeability of film to O₂ has the potential to stimulate aerobic microorganisms, including yeasts and molds, thereby resulting in DM losses and aerobic deterioration. Recently, Borreani and Tabacco (2008) found that insertion of an O₂-limiting barrier within the polyethylene wrap reduced losses of DM during storage and had the potential to reduce the number of wrapping layers required for good fermentation and storage, which may provide a cost incentive to producers. Our objectives for this project were to test the effects of delayed wrapping on silage fermentation, storage characteristics, and the nutritive value of baled alfalfa silages. To accomplish this, large-round bales of alfalfa were wrapped in plastic film within 4 h of baling (d 0), or after delays of 1, 2, or 3 d. A secondary objective was to evaluate a prototype bale wrap containing

an O₂-limiting barrier (OB) against the identical polyethylene wrap without the O₂ barrier (SUN).

MATERIALS AND METHODS

Field, Storage, and Sampling Procedures

Description of Field Site and Experimental Layout. An 8.0-ha site on the University of Wisconsin Marshfield Agricultural Research Station, located near Stratford, Wisconsin (44°7'N, 90°1'W), was selected for the experiment. The field site was planted to Croplan Rebound 6.0 alfalfa (Winfield Solutions LLC, St. Paul, MN) at a seeding rate of 13.4 kg/ha during 2013. During 2014, the second cutting from this site was mowed at 25% bloom on August 5, 2014, with a 4.9-m-wide Case-International Harvester Model DC163 Hydroswing mower-conditioner (CNH Industrial America LLC, Racine, WI) equipped with metal conditioning rollers. Subsequently, the field was raked at 0930 h on August 7 with a Kuhn Model GA 4220 TH Masterdrive side-delivery rake (Kuhn S.A., Saverne, France). Sixty-four round bales bound with net wrap (2 revolutions) were made between 1400 and 1600 h on the same day with a New Holland BR740A Crop Cutter round baler (CNH Industrial America LLC); the option for cutting alfalfa stems into shorter lengths was not engaged during this study. Prior to initiating the experiment, the field site was subdivided primarily on the basis of topography (slope), into 4 experimental blocks of approximately equal size (2 ha); therefore, a total of 16 bales were made per field block for the study.

Description of Experimental Treatments. Silage bale wraps used in this study included SUNFILM (750 mm × 1,500 m × 25 µm; AEP Industries Inc., Mt. Top, PA), which is a commercially available product commonly used throughout the United States (SUN), and a prototype film produced identically, but with an O₂-limiting barrier (Kuraray America Inc., Pasadena, TX) inserted within the wrap (OB). Oxygen transmission rates for a single layer measured at 1 atm of pressure, 20°C, and 65% relative humidity were 6,931 and 198 cm³/m²·d for SUN (MOCON Testing Service, Minneapolis, MN) and OB (Kuraray America Inc.), respectively. This study was designed as a randomized complete block with a 2 × 4 factorial arrangement of treatments that included 2 wrap types (SUN or OB) and 4 wrapping times (d 0, or after 1-, 2-, or 3-d delays). As described, 8 treatment combinations were represented within each field block, and 2 bales were produced per block for each treatment combination. Treatment assignments within each block were randomized before the trial began, such that successive bales discharged from the baler were not assigned to

like treatment combinations, unless dictated by the a priori randomization.

Initial Bale Processing and Sampling. All bales were measured and weighed (± 0.2 kg). For bales assigned to be wrapped without delay (d 0), four 0.61-m-deep core samples (0.025-m diameter) were obtained from one side of each bale at 1700 h using a Uni-Forage Sampler (Star Quality Samplers, Edmonton, AB, Canada) fitted to an electric drill. Air was purged from the sample holes with spray-foam insulation; however, filling of holes was terminated well before insulation was visible at the mouth of the sampling hole to prevent the wet foam insulation from directly contacting the polyethylene film when bales were wrapped shortly thereafter. All core samples were composited by bale (~ 350 g/bale; wet basis), sealed in 3.8-L plastic freezer bags, placed on ice in insulated coolers, and taken to the research laboratory, where a 50-g subsample was removed and dried overnight in a convection oven at 105°C to determine the moisture concentration of the forage within each bale. The remainder of the composite sample from each bale was immediately placed in an ultralow freezer (-80°C) to suspend respiration pending further processing and analysis.

Beginning at 1800 h on August 7, bales assigned to be wrapped without delay (d 0) were wrapped with the assigned film type (SUN or OB), and placed on a concrete storage pad with an east to west orientation. Transport from the field, weighing, sampling, and wrapping represented an approximate 4-h time lag between baling and wrapping of these bales, which is consistent with good production management. Bales were not stacked on top of each other after they were wrapped. Silage wraps were applied with an individual (single-bale) wrapper (model 995 TSR, McHale Engineering Limited, Ballinrobe, Co. Mayo, Ireland) that was preprogrammed to apply 7 film layers (28 table revolutions) to each bale. This wrapping protocol would be expected to provide good security for long-term storage, and is consistent with local production management whenever long-term (7 to 10 mo) storage is projected. Borreani and Tabacco (2008) have suggested that insertion of an O_2 -limiting barrier within polyethylene bale wraps has the potential to reduce the number of wrapping layers required for good fermentation and storage, thereby potentially providing a cost incentive to producers. Our wrapping protocol was intentionally selected to establish a conservative baseline for comparing reduced numbers of wrapping layers in future studies. Immediately after bale wrapping was completed, 1 of the 2 bales per block assigned to the same wrap type was fitted with a thermocouple that was placed in the geometric center of the bale. The small hole where the

thermocouple wire exited the bale wrap was immediately covered with appropriate tape for repairing silage plastics; wrapped bales were inspected weekly throughout the storage period to ensure the integrity of the tape covering this exit hole.

Processing and sampling procedures for bales assigned to 1-, 2-, or 3-d time delays were conducted similarly, beginning with core sampling at 1300 h and wrapping with film at 1400 h daily. Therefore, initial bale weights and all other chemical analyses conducted on a prestorage basis represent the forage or conditions within the bale at the time each bale was wrapped, and not at the time it was baled. After wrapping, bales were monitored for internal bale temperature at approximately 1300 h daily with a handheld Omega 450 AKT Type K thermocouple thermometer (Omega Engineering, Stamford, CT) until the trial was terminated with a final sampling of all bales on November 13, 2014. Internal bale temperatures were then summarized to yield 3 temperature related response variables: (1) internal bale temperature at the time bales were wrapped, (2) maximum internal bale temperature, and (3) 23-d average temperature, which was based on the observation that no internal bale temperature exceeded 30°C beyond 23 d of storage.

Poststorage Sampling

Procedures for processing silage bales after a 97-d storage period were initiated by reweighing each silage bale. The film wrap was removed from 6 randomly selected bales to establish a mean correction factor (3.3 ± 0.12 kg) that could be applied to all bales to correct final bale weights for the weight of the film wrap. After weighing, eight 0.61-m-deep core samples (0.025-m diameter) were taken from the side of the bale that was opposite where initial cores were obtained before storage. Core samples from each bale were composited (~ 600 g), thoroughly mixed, and a 50-g subsample was immediately dried overnight in a convection oven at 105°C to determine the final moisture concentration of each bale. Recoveries of DM following silage fermentation and storage were calculated from DM weights of each bale on a pre- and poststorage basis; because bales were sampled initially (pre-storage) at the time they were wrapped, calculated recoveries of DM represent storage efficiencies from the time of wrapping only, and do not reflect any respiratory losses before bale wrapping. The remainder of each silage sample was sealed in a plastic freezer bag and placed in an ultralow (-80°C) freezer to suspend respiration pending further analysis of nutritive value, pH, and silage fermentation products.

Laboratory Analyses

Silage. On a pre-ensiled basis, a 25-g subsample was removed from each sealed freezer bag after thorough mixing, and initial pH of each bale was determined by adding 100 mL of deionized water and macerating for 30 s in a kitchen blender. The macerated contents were then filtered through 2 layers of cheesecloth, and the pH was determined with a bench-top pH meter (Orion-3Star, Thermo Fisher Scientific Inc., Waltham, MA). The remaining portion of the composite sample from each bale (~275 g) was lyophilized and then ground through a Thomas Model 4 Wiley Mill (Thomas Scientific, Swedesboro, NJ) fitted with a 1-mm screen. Ground, lyophilized samples were retained for subsequent analysis of nutritive value, buffering capacity (**BC**), water-soluble carbohydrates (**WSC**), and starch. Buffering capacity was reported as milliequivalents of HCl per kilogram of forage DM needed to reduce pH from 6.0 to 4.0 (Muck and Walgenbach, 1985; Coblenz and Muck, 2012). Water-soluble carbohydrates were extracted from a 0.25-g ground subsample in 150 mL of deionized water for 2 h, and then gravity-filtered through Whatman #1 filter paper (GE Healthcare UK Limited, Little Chalfont, Buckinghamshire, UK). Concentrations of WSC were quantified using the phenol-sulfuric acid reaction, with final concentrations of WSC determined colorimetrically (Dubois et al., 1956). Concentrations of starch were determined by enzymatic hydrolysis of starch molecules with amyloglucosidase. D-Glucose monomers and O₂ were converted by glucose oxidase to D-glucono- δ -lactone and H₂O₂; subsequently, the H₂O₂ was oxidized electrochemically to yield a signal current (model 2700D Bioanalyzer, Yellow Springs Instrument Co., Yellow Springs, OH), which was calibrated to liberated peroxide from known standards (YSI, 2000).

For postensiled samples, sample processing and analysis procedures generally were similar to those described for pre-ensiled samples. However, BC was determined only on a pre-ensiled basis and omitted for all silage samples obtained after the 97-d storage period. Concentrations of fermentation products and NH₃-N within all silage samples were determined by Cumberland Valley Analytical Services (Maugansville, MD).

Nutritive Value. All lyophilized, ground forage samples were analyzed sequentially for NDF, ADF, hemicellulose, cellulose, and ADL using batch procedures outlined by Ankom Technology Corp. (Macedon, NY) for an Ankom200 Fiber Analyzer. Sodium sulfite and heat-stable α -amylase were omitted from the NDF solution. Concentrations of total N within each sample

were determined with a rapid combustion procedure (AOAC International, 1998; method 990.03; Elementar Americas Inc., Mt. Laurel, NJ), followed by conversion to CP using a factor of 6.25. Pools of CP that were insoluble in neutral and acid detergent (**NDICP** and **ADICP**, respectively) were determined similarly following nonsequential digestion in each respective solution. For this application, the NDF solution did not contain heat-stable α -amylase or sodium sulfite, the latter of which was omitted because it cleaves disulfide bonds and dissolves cross-linked proteins, thereby reducing protein recovery from NDF residues (Van Soest et al., 1991). Whole-plant ash was determined by combusting 1.0-g samples of lyophilized forage in a muffle furnace at 500°C for 6 h. Calculations of TDN for all forages were based on the summative equation (Weiss et al., 1992; NRC, 2001) using the ADL option for estimating truly digestible fiber.

Statistics

Data were analyzed by PROC MIXED of SAS (2010, version 9.3, SAS Institute Inc., Cary, NC) as a randomized complete block design with a 2 $\times$ 4 factorial arrangement of 2 silage wraps (OB or SUN) and 4 wrapping times (d 0, or after 1-, 2-, or 3-d delays). There were 2 bales per treatment combination within each block, and blocks (4) were declared random throughout all analyses. Orthogonal contrasts were used to evaluate differences between wrapping time delays and wrap types: (1) delayed wrapping (1, 2, or 3 d) vs. control (d 0); (2) linear effect of wrapping delay; (3) quadratic effect of wrapping delay; and (4) OB vs. SUN. No evidence was found of an interaction between silage wraps and time delay across response variables; therefore, only main-effect means are reported and discussed. Furthermore, wrap types (OB vs. SUN) did not differ ($P \geq 0.072$) for any response variable evaluated. As a result, mean comparisons for wrap types are reported in the tables, but are not discussed in the text.

Regressions of silage fermentation products or indices of nutritive value on internal bale temperatures at the time bales were wrapped in polyethylene film were conducted by PROC REG of SAS (2010). To conduct these regressions ($n = 32$), the dependent variable (y-axis) represents the mean concentration calculated from the pair of like bales obtained from each interactive treatment combination within each field replication. The independent variable (x-axis) is the internal temperature measured within one bale within the same pair that was assigned a priori to be fitted with a thermocouple. Statistical significance was declared at the $P = 0.05$ level of confidence.

RESULTS AND DISCUSSION

Bale Characteristics

Prestorage. It should be emphasized that wet bale weights, initial DM concentrations of alfalfa forages, and calculated bale DM weights and DM densities were based on weights and core samples obtained immediately before silage wraps were applied (Table 1); therefore, any losses of DM via respiration that occurred before wrapping are not directly quantified. The only difference between treatments for initial bale characteristics was associated with wet bale weights, which were greater for bales wrapped on d 0 compared with those wrapped after a time delay (488 vs. 468 kg; $P = 0.005$). Wet bale weights also declined linearly ($P < 0.001$) as the time delay was extended. However, these responses were not detected ($P \geq 0.349$) when bale weights were reported on a DM basis.

Overall, the mean initial bale moisture concentration (59.1%) was slightly greater than the range (45 to 55%) suggested by Shinnors (2003), but was well within the scope of many recent baled silage experiments (Nicholson et al., 1991; McCormick et al., 1998; Han et al., 2004; Hancock and Collins, 2006). Increasing the moisture concentration within silages positively affects the rate of fermentation, as well as concentrations and proportions of various fermentation products, which result in a more acidic final silage pH (Muck, 1990). The mean DM density of all silage bales (134 kg of DM/m³) was somewhat less than reported by Han et al. (2004; 167 to 207 kg of DM/m³), Hancock and Collins

(2006; 187 to 207 kg of DM/m³), or Coblenz et al. (2014; 151 to 210 kg of DM/m³) in other experiments with alfalfa baled silage. Extension recommendations often encourage the production of dense silage bales to improve fermentation and storage efficiency, primarily by eliminating air from the silage mass. A frequently mentioned target for DM density of baled silages is 162 kg of DM/m³ (10 lb of DM/ft³; Jennings, 2011), which often can be increased by slowing ground speed during baling operations. Our relatively low DM densities likely resulted from a procedural compromise in which baler ground speed was maintained at a rate suitable to produce 64 bales in less than 2 h, thereby avoiding the creation of a bale moisture gradient across field blocks.

Poststorage Bale Characteristics

Final wet bale weights (Table 2) were greater for bales wrapped the same day as baling compared with those wrapped after a 1-, 2-, or 3-d time delay (467 vs. 453 kg; $P = 0.025$), and final wet bale weights declined linearly ($P = 0.001$) with increasing time delay. Final concentrations of bale moisture tended to exhibit a linear decline with wrapping time delay ($P = 0.058$). Neither the amount of DM recovered per bale (overall mean = 184 kg of DM; $P \geq 0.178$), nor the percentage of DM recovered (overall mean = 95.6%; $P \geq 0.074$), were affected by treatment; however, the DM recovery for bales wrapped on d 0 tended to differ from those wrapped with 1-, 2-, or 3-d time delays (93.3 vs. 96.4%; $P = 0.074$).

Table 1. Physical characteristics^{1,2} of 64 alfalfa silage bales at the time of wrapping in stretch film with (OB) or without (SUN) an O₂-limiting barrier, and after wrapping delays as long as 3 d

Treatment	Width, m	Diameter, m	Volume, m ³	Wet weight, kg	Bale moisture, %	DM weight, kg of DM	DM density, kg of DM/m ³
Wrapping delay, d							
0	1.20	1.25	1.46	488	59.6	197	135
1	1.18	1.25	1.45	486	61.0	189	131
2	1.19	1.24	1.45	460	56.6	199	138
3	1.18	1.25	1.45	459	59.1	187	130
SEM	0.008	0.006	0.020	6.6	1.10	4.7	3.6
Wrap type							
OB	1.19	1.25	1.46	471	59.0	193	133
SUN	1.19	1.25	1.45	476	59.2	194	134
SEM	0.007	0.004	0.016	5.2	0.83	3.3	2.6
Contrast ³ ($P > F$)							
(1) Delay vs. control	0.113	0.894	0.470	0.005	0.566	0.349	0.575
(2) Delay: linear	0.296	0.882	0.616	<0.001	0.207	0.355	0.560
(3) Delay: quadratic	0.471	0.723	0.572	0.991	0.589	0.656	0.570
(4) OB vs. SUN	0.464	0.933	0.726	0.444	0.887	0.824	0.752

¹Bale width and diameter measured immediately after baling; bale volume calculated on the basis of those measurements.

²Bale weight, dry weight, and DM density were determined at the time bales were wrapped in film, and do not include any changes that may have occurred during the delay before wrapping.

³Contrasts: (1) delay vs. control, bales wrapped after a 1-, 2-, or 3-d delay vs. those wrapped the same day they were baled; (2) delay: linear, linear effect of wrapping delay; (3) delay: quadratic, quadratic effect of wrapping delay; and (4) OB vs. SUN wrap.

Table 2. Temperature and poststorage physical characteristics of 64 alfalfa silage bales wrapped in stretch film with (OB) or without (SUN) an O₂-limiting barrier, and after wrapping delays as long as 3 d

Treatment	Wet weight, kg	Bale moisture, %	DM recovered, kg	DM recovery, %	Internal bale temperature, ¹ °C		
					At wrapping	Maximum	23-d average
Wrapping delay, d							
0	467	60.7	183	93.3	34.9	38.1	29.7
1	467	61.0	182	96.6	47.3	49.2	33.9
2	445	56.9	191	96.3	53.5	59.3	37.7
3	447	59.7	180	96.2	63.9	66.7	39.6
SEM	6.1	0.92	3.8	1.59	1.10	0.96	0.43
Wrap type							
OB	453	59.5	183	95.5	49.7	53.1	35.4
SUN	460	59.7	185	95.6	50.1	53.6	35.1
SEM	4.7	0.70	2.7	1.20	0.80	0.69	0.33
Contrast ² (<i>P</i> > <i>F</i>)							
(1) Delay vs. control	0.025	0.122	0.799	0.074	<0.001	<0.001	<0.001
(2) Delay: linear	0.001	0.058	0.953	0.203	<0.001	<0.001	<0.001
(3) Delay: quadratic	0.831	0.147	0.178	0.248	0.338	0.066	0.008
(4) OB vs. SUN	0.204	0.829	0.650	0.939	0.715	0.598	0.530

¹Internal bale temperature: maximum, maximum temperature recorded on any day during the 99-d storage period; 23-d average, and mean bale temperature during the first 23 d of storage.

²Contrasts: (1) delay vs. control, bales wrapped after a 1-, 2-, or 3-d delay vs. those wrapped the same day they were baled; (2) delay: linear, linear effect of wrapping delay; (3) delay: quadratic, quadratic effect of wrapping delay; and (4) OB vs. SUN wrap.

Internal Bale Temperatures

Internal bale temperatures (Table 2) responded predictably to extended exposure to air before wrapping, with availability of O₂ supporting continuing respiration within the bale that resulted in sharply elevated internal bale temperatures. The internal bale temperature for the positive (0-d) control was less than those bales wrapped after extended time delays (34.9 vs. 54.9°C; *P* < 0.001), and temperatures increased linearly (*P* < 0.001) with length of delay. Similar responses were observed for maximum internal bale temperature, which generally occurred 1 to 3 d after bales were wrapped, and was an average of 3.5°C greater across all bales compared with temperatures measured at the time of wrapping. No bale exceeded the 30°C threshold commonly associated with formation of Maillard products in heated hays (Coblentz et al., 2010) or silages for more than 23 d; however, internal bale temperatures subsided more slowly after wrapping following longer time delays. This observation is reflected in 23-d mean bale temperatures, which were about 10°C greater for a 3-d delay compared with no delay, and increased with strong linear (*P* < 0.001) and quadratic (*P* = 0.008) effects of time delay.

Prestorage Ensiling Characteristics

The pH of baled alfalfa forages at the time they were wrapped with film did not vary (overall mean = 6.22; *P* ≥ 0.459) on the basis of time delay (Table 3). Buffering

capacity was greater when wrapping was delayed for 1, 2, or 3 d compared with no delay (480 vs. 421 mEq/kg of DM; *P* < 0.001), and it increased in a strong linear (*P* < 0.001) relationship with length of wrapping delay. These results suggest that alfalfa becomes more highly buffered when spontaneous heating occurs before bale wrapping, thereby compounding an existing obstacle to good silage fermentation. Legumes in general, and alfalfa specifically, are known to be buffered more extensively than grasses, largely because of greater concentrations of organic acids, and to a lesser extent, proteins (McDonald et al., 1991). Several factors are known to reduce BC in alfalfa, most of which are consistent with poorer forage quality, such as plant maturity, stem percentage, and rain damage (Muck and Walgenbach, 1985; Coblentz and Muck, 2012). Conceptually, wrapping delays also should affect nutritive value negatively, primarily through respiration of sugars, which indirectly increases concentrations of forage fiber components (Rotz and Muck, 1994). However, the net effect of respiratory activity on BC was a sharp (21%) increase after a 3-d delay in wrapping compared with the positive (0-d) control.

Concentrations of WSC (Table 3) were greater when bales were wrapped in film within 4 h of baling compared with bales wrapped after a time delay (5.3 vs. 4.4%; *P* < 0.001); in addition, WSC declined linearly (*P* < 0.001) with the length of time delay. Responses for concentrations of starch were similar, with an overall linear (*P* = 0.027) effect of time delay detected. However, unlike concentrations of WSC, bales wrapped

Table 3. Prestorage ensiling characteristics for 64 large-round bales of alfalfa baled silage wrapped in stretch film either with (OB) or without (SUN) an O₂-limiting barrier, and after wrapping delays as long as 3 d¹

Treatment	Initial pH	Buffering capacity, mEq/kg of DM	WSC ² , % of DM	Starch, % of DM
Wrapping delay, d				
0	6.25	421	5.3	0.68
1	6.18	451	4.6	0.66
2	6.23	479	4.5	0.55
3	6.22	510	4.0	0.57
SEM	0.059	6.1	0.14	0.044
Wrap type				
OB	6.24	461	4.6	0.62
SUN	6.20	469	4.6	0.61
SEM	0.050	4.3	0.14	0.032
Contrast ³ (<i>P</i> > <i>F</i>)				
(1) Delay vs. control	0.459	<0.001	<0.001	0.080
(2) Delay: linear	0.813	<0.001	<0.001	0.027
(3) Delay: quadratic	0.586	0.960	0.292	0.590
(4) OB vs. SUN	0.263	0.175	0.488	0.914

¹Bale moisture, initial pH, BC, WSC and starch were determined at the time bales were wrapped in film, and reflect any changes that occurred during the structured delay periods before wrapping.

²WSC, water-soluble carbohydrates.

³Contrasts: (1) delay vs. control, bales wrapped after a 1-, 2-, or 3-d delay vs. those wrapped the same day they were baled; (2) delay: linear, linear effect of wrapping delay; (3) delay: quadratic, quadratic effect of wrapping delay; and (4) OB vs. SUN wrap.

promptly compared with those wrapped following a time delay only tended to differ (0.68 vs. 0.59%; *P* = 0.080) with respect to concentrations of starch.

Under ideal conditions, alfalfa is difficult to ensile because of its high BC and relatively low concentrations of the WSC that are required for production of lactic acid as the principal desired fermentation product (McDonald et al., 1991). Based on these results, time delays before bales are wrapped make ensiling alfalfa even more challenging because of the strong linear effects on both BC and WSC, which were positive and negative, respectively. Wrapping following any significant time delay results in an alfalfa forage that is more resistant to pH change and has less WSC available as substrate for production of silage fermentation acids, thereby increasing the problematic nature of silage fermentation.

Regressions of WSC and BC on Internal Bale Temperature

The relatively clear cause-and-effect relationship between wrapping delay and internal bale temperature for these silage bales has been described (Table 2). This spontaneous heating response occurs primarily via respiration of nonstructural carbohydrate into CO₂, H₂O, and heat (Rotz and Muck, 1994), and is commonly observed in moist hays stored in large-round bales (Coblentz and Hoffman, 2009a). Figure 1 depicts the inverse relationship between pre-ensiled concentrations of WSC and the internal bale temperature at the time film wrap was applied ($y = -0.039x + 6.5$; $R^2 = 0.634$;

$P < 0.001$), and illustrates the declining pool of WSC available to support silage fermentation whenever bales are not wrapped promptly. In contrast, a positive linear relationship ($y = 2.98x + 316$; $R^2 = 0.759$; $P < 0.001$) was observed between BC and internal bale temperature (Figure 2), which to our knowledge has not been demonstrated previously. Within this study, both of the previously stated limitations for alfalfa silage fermentation (low concentrations of WSC, high BC) were clearly exacerbated as simple linear functions of respiratory heat production before bale wrapping.

Figure 1. Linear regression of water-soluble carbohydrates (WSC) on internal bale temperature at the time alfalfa silage bales were wrapped with polyethylene films containing either an O₂ barrier or no barrier at Marshfield, Wisconsin.

Figure 2. Linear regression of buffering capacity (BC) on internal bale temperature at the time alfalfa silage bales were wrapped with polyethylene films containing either an O₂ barrier or no barrier at Marshfield, Wisconsin.

Silage Fermentation Characteristics

NH₃-N. On a percentage of DM basis, concentrations of NH₃-N in these fermented alfalfa silages (Table 4) were greater in bales wrapped without delay compared with those wrapped 1, 2, or 3 d after baling (0.68 vs. 0.52%; $P < 0.001$). Concentrations of NH₃-N declined from 0.68 to 0.44% when wrapping was delayed by 2 d, but increased to 0.57% after a 3-d delay, which resulted in both linear ($P = 0.001$) and quadratic ($P < 0.001$) overall effects of wrapping delay. Overall, NH₃-N comprised between 12.4 and 19.0% of the total N within our baled silages. A common management target for NH₃-N is $\leq 12\%$ of silage N (McDonald and Edwards, 1976; Mahanna and Chase, 2003); however, larger percentages are indicative of undesirable activity of proteolytic clostridia within the silages (McDonald et al., 1991).

Final pH. The final pH of alfalfa silages (Table 4) was most acidic when wrapping occurred on d 0 or after a 1-d delay. Overall, delayed wrapping (1, 2, or 3 d) resulted in a greater final pH than bales wrapped promptly after baling (5.78 vs. 5.70; $P = 0.004$); in addition, final pH increased with both linear ($P < 0.001$) and quadratic ($P = 0.010$) effects of wrapping delay, demonstrating an increase of 0.1 pH unit per d for bales wrapped after 2 or 3 d compared with those wrapped 1-d postbaling. Reports describing the effects of wrapping delay on final silage pH are limited; however, Moshtaghi Nia and Wittenburg (2000) reported a less acidic pH for barley silages sampled after 64 d of storage whenever the initial bale wrapping was delayed for 19 h (pH = 5.69) compared with 2 or 10 h, whose responses were similar (mean pH = 4.77). Although

not tested statistically, it is interesting that the final pH for bales wrapped without time delay and those wrapped after 1 d were very similar (5.70 and 5.68, respectively), especially given the large advantages observed for production of total acids (4.63 vs. 3.19%), lactic acid (1.88 vs. 1.59%), and acetic acid (1.47 vs. 0.77%) by bales wrapped without time delay. However, acetic and butyric acids are weaker than lactic acid, and formation of butyric acid often comes at a cost of 2 lactic acid molecules, all of which may have contributed to this observation.

Silage Fermentation Acids. Total fermentation acids (Table 4) were greater for bales wrapped the same day baling occurred compared with bales wrapped after a time delay (4.64 vs. 2.26%; $P < 0.001$), and concentrations of total acids declined with linear ($P < 0.001$) and quadratic ($P < 0.001$) effects of time delay. Concentrations of lactic acid were greatest in bales wrapped without time delay (1.88 vs. 1.00%; $P < 0.001$), and declined in a strong linear ($P < 0.001$) pattern with the length of time delay, reaching a minimum of 0.67% after 3 d. In contrast to concentrations of total fermentation acids, lactic acid did not demonstrate a quadratic effect ($P = 0.180$) of time delay. The linear decline in production of lactic acid is largely predictable because WSC is a required substrate, and sugars were oxidized during the respiratory activity that occurred during 1-, 2-, and 3-d wrapping delays.

The quadratic effect observed for production of total fermentation acids was likely associated with increased production of less desirable or undesirable fermentation acids, particularly after a 2-d wrapping delay. Within this context, overall linear ($P < 0.001$) and quadratic ($P \leq 0.021$) effects were observed for declining concentrations of acetic, propionic, butyric, and isobutyric acids, with slight increases occurring in each case with a 3-d wrapping delay compared with a 2-d delay. For bales wrapped without a time delay, production of acetic (1.47 vs. 0.76%; $P < 0.001$), propionic (0.28 vs. 0.07%; $P < 0.001$), and butyric (0.99 vs. 0.38%; $P < 0.001$) acids was greater than in bales wrapped following time delays.

Of these less desirable or undesirable acids, the production of butyric acid is most problematic; this suggests significant activity by saccharolytic clostridia, which ferment sugars and organic acids, yielding butyric acid as a primary end product (McDonald et al., 1991). Elevated concentrations of both butyric acid and NH₃-N (discussed previously) are consistent with greater clostridial activity within bales wrapped without time delay. Although circumstantial in nature, these observations are further corroborated by a tendency for poorer DM recoveries in bales wrapped without time delay compared with recoveries from bales where wrap-

Table 4. Fermentation characteristics¹ for 64 alfalfa silage bales wrapped in stretch film either with (OB) or without (SUN) an O₂-limiting barrier, and after wrapping delays as long as 3 d

Treatment	NH ₃ -N, % of DM	NH ₃ -N, % of N	Final pH	Total acids, % of DM	Lactic, % of DM	Acetic, % of DM	Propionic, % of DM	Butyric, % of DM	Isobutyric, % of DM	Methanol, % of DM	Ethanol, % of DM
Wrapping delay, d											
0	0.68	19.0	5.70	4.64	1.88	1.47	0.28	0.99	0.02	0.19	0.29
1	0.54	15.0	5.68	3.13	1.59	0.77	0.10	0.67	0.01	0.20	0.16
2	0.44	12.4	5.78	1.54	0.73	0.61	0.04	0.12	0.05	0.23	0.09
3	0.57	16.2	5.89	2.11	0.67	0.91	0.08	0.35	0.11	0.24	0.09
SEM	0.031	0.84	0.039	0.221	0.135	0.091	0.016	0.089	0.012	0.020	0.009
Wrap type											
OB	0.55	15.6	5.77	2.74	1.22	0.89	0.11	0.48	0.04	0.22	0.16
SUN	0.56	15.8	5.76	2.96	1.22	0.98	0.14	0.57	0.05	0.21	0.16
SEM	0.024	0.66	0.035	0.170	0.120	0.076	0.011	0.063	0.009	0.017	0.006
Contrast ² (<i>P</i> > <i>F</i>)											
(1) Delay vs. control	<0.001	<0.001	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	0.010	0.012	<0.001
(2) Delay: linear	0.001	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001
(3) Delay: quadratic	<0.001	<0.001	0.010	<0.001	0.180	<0.001	<0.001	0.003	0.021	0.756	<0.001
(4) OB vs. SUN	0.714	0.758	0.592	0.279	0.999	0.231	0.072	0.314	0.347	0.414	0.969

¹Total fermentation acids were calculated as the sum of lactic, acetic, propionic, butyric, and isobutyric acids. Each silage sample also was analyzed for 2-butanol, methyl acetate, ethyl acetate, propyl acetate, ethyl lactate, propyl lactate, and 1,2-propanediol; however, each of these fermentation products were either not detectable or present in only trace concentrations.

²Contrasts: (1) delay vs. control, bales wrapped after a 1-, 2-, or 3-d delay vs. those wrapped the same day they were baled; (2) delay: linear, linear effect of wrapping delay; (3) delay: quadratic, quadratic effect of wrapping delay; and (4) OB vs. SUN wrap.

ping was delayed (93.3 vs. 96.4%; $P = 0.074$; Table 2). Theoretically, an additional side effect of converting 2 lactate molecules into butyrate is a 51% loss of DM associated with that specific conversion, primarily through formation of CO_2 , H_2 , and H_2O (McDonald et al., 1991). It remains unclear why evidence of clostridial activity was greatest when bales were wrapped without a time delay. However, this silage fermentation response could be related to a combination of factors, including (1) a moderately high moisture concentration (59.6%) that slightly exceeded common recommendations for baled silage (45 to 55%; Shinnors, 2003), but was substantially less than recommendations for chopped alfalfa silage ($\leq 70\%$; Muck et al., 2003); (2) slower and less extensive silage fermentation in baled silages because the alfalfa was baled and sealed on a whole-plant basis that required diffusion of sugars to lactic-acid-producing bacteria adhered to the outside of the plants (Nicholson et al., 1991; Muck et al., 2003; Savoie and Jofriet, 2003); (3) a final pH that was insufficiently acidic to inhibit the activity of clostridial bacteria, which often is thought to occur at about pH = 4.2 (McDonald et al., 1991); and (4) greater concentrations of WSC and lactic acid than observed within time-delayed wrapping treatments, which are required substrates for formation of butyrate. Regardless, these results suggest that baled alfalfa silages may be more susceptible to clostridial fermentation than precision-chopped silages.

In contrast to other fermentation acids, concentrations of isobutyric acid generally increased from minimal and static concentrations ($\leq 0.05\%$) with wrapping delays up to 2 d to 0.11% after a 3-d delay. These responses yielded linear ($P < 0.001$) and quadratic ($P = 0.021$) effects of time delay, and bales wrapped without delay contained less isobutyric acid than those with 1-, 2-, or 3-d delays (0.02 vs. 0.06%; $P = 0.010$). Isobutyric acid is an oxidation product of valine and has been found in measurable concentrations in clostridial alfalfa silages (Ohshima et al., 1979).

Methanol and Ethanol. Overall, concentrations of methanol were low (overall mean = 0.22%), but were greater in silages wrapped after a time delay compared with those fermented without a time delay (0.22 vs. 0.19%; $P = 0.012$), and increased linearly ($P = 0.002$) in response to wrapping delay. In contrast, concentrations of ethanol were greatest when bales were wrapped without time delay (0.29 vs. 0.11%; $P < 0.001$), and declined with both linear ($P < 0.001$) and quadratic ($P < 0.001$) effects as time delays were extended to 3 d.

Regressions of Fermentation Products, and pH on Internal Bale Temperature at Wrapping. Concentrations of total fermentation acids and most major individual silage acids declined with internal

bale temperature (Figures 3, 4, 5, and 6); however, the relationships were quadratic for total fermentation acids ($y = 0.0042x^2 - 0.50x + 17.1$; $R^2 = 0.725$; $P < 0.001$) and acetic acid ($y = 0.0022x^2 - 0.24x + 7.1$; $R^2 = 0.646$; $P < 0.001$), but linear for lactic acid ($y = -0.046x + 3.5$; $R^2 = 0.663$; $P < 0.001$). Concentrations of butyric acid also declined linearly with spontaneous heating ($y = -0.024x + 1.7$; $R^2 = 0.375$; $P < 0.001$); however, responses were more erratic, resulting in a poorer coefficient of determination than observed for total, lactic, or acetic acids. Several minor end products of silage fermentation also exhibited close relationships with internal bale temperature (data not shown). Concentrations of propionic acid declined in a quadratic relationship ($y = 0.00040x^2 - 0.046x + 1.4$; $R^2 = 0.711$; $P < 0.001$) with bale temperature, whereas the opposite (positive) response was observed for isobutyric acid ($y = 0.00016x^2 - 0.013x + 0.3$; $R^2 = 0.566$; $P < 0.001$). Although concentrations of ethanol were relatively low ($< 0.35\%$), this end product exhibited the closest relationship to internal bale temperature of any silage fermentation product evaluated ($y = 0.00025x^2 - 0.031x + 1.1$; $R^2 = 0.856$; $P < 0.001$). Overall, the final pH of baled silages in this study (Figure 7) increased linearly ($y = 0.0072x + 5.4$; $R^2 = 0.411$; $P < 0.001$) with internal bale temperature, which reflects the decreased production of most fermentation acids as a function of spontaneous heating before bale wrapping.

Nutritive Value

Preensiled. On a preensiled basis, concentrations of whole-plant ash and all fiber components except

Figure 3. Quadratic regression of total silage fermentation acids after a 97-d storage period on internal bale temperature at the time alfalfa silage bales were wrapped with polyethylene films containing either an O_2 barrier or no barrier at Marshfield, Wisconsin.

Figure 4. Linear regression of lactic acid after a 97-d storage period on internal bale temperature at the time alfalfa silage bales were wrapped with polyethylene films containing either an O₂ barrier or no barrier at Marshfield, Wisconsin.

hemicellulose were greater ($P \leq 0.017$) after 1-, 2-, or 3-d wrapping delays compared with bales wrapped the same day they were baled (Table 5). For each of these nutritional indices, concentration increases also exhibited linear ($P \leq 0.002$) effects of time delay. Generally, the magnitude of increased NDF, ADF, cellulose, ADL, and ash concentrations was relatively modest across a maximum 3-d wrapping delay, amounting to 2.8, 2.4, 1.5, 0.65, and 0.5 percentage units of DM, respectively. Fiber components and ash are generally considered relatively inert during spontaneous heating, and concentrations typically increase indirectly via oxidation of other often highly digestible forage components, particularly sugars (Rotz and Muck, 1994; Coblenz and Hoffman, 2009b). Hemicellulose exhibited only a quadratic re-

Figure 5. Quadratic regression of acetic acid after a 97-d storage period on internal bale temperature at the time alfalfa silage bales were wrapped with polyethylene films containing either an O₂ barrier or no barrier at Marshfield, Wisconsin.

Figure 6. Linear regression of butyric acid after a 97-d storage period on internal bale temperature at the time alfalfa silage bales were wrapped with polyethylene films containing either an O₂ barrier or no barrier at Marshfield, Wisconsin.

sponse to wrapping time delays ($P = 0.001$), but no other contrasts were detected for this fiber component ($P \geq 0.111$). Although it is widely accepted that spontaneous heating of forages increases concentrations of CP that are insoluble in neutral or acid detergent (Licita et al., 1996), which also reduces their bioavailability within ruminants (Van Soest, 1982), this was not clearly demonstrated on a pre-ensiled basis. Concentrations of CP were not affected by wrapping time delay (overall mean = 22.3%; $P \geq 0.243$), whereas NDICP exhibited both linear ($P < 0.001$) and quadratic ($P < 0.001$) effects, and ADICP exhibited only a quadratic ($P = 0.027$) response. For both NDICP and ADICP, these responses are difficult to relate decisively to the heating associated with wrapping time delays, and the lack of

Figure 7. Linear regression of silage pH after a 97-d storage period on internal bale temperature at the time alfalfa silage bales were wrapped with polyethylene films containing either an O₂ barrier or no barrier at Marshfield, Wisconsin.

Table 5. Nutritive value (% of DM) of alfalfa silage bales sampled immediately before wrapping in stretch film either with (OB) or without (SUN) an O₂-limiting barrier, and after wrapping delays as long as 3 d

Treatment	NDF	ADF	HEMI ¹	Cellulose	ADL	Ash	CP	NDICP ¹	ADICP ¹	TDN ²
Wrapping delay, d										
0	45.7	30.3	15.4	24.0	5.82	10.7	22.1	4.82	2.06	58.3
1	45.7	31.1	14.6	24.5	5.99	10.9	22.4	4.24	1.99	57.6
2	46.6	31.5	15.0	25.0	6.11	11.0	22.2	4.69	1.93	57.3
3	48.5	32.7	15.8	25.5	6.47	11.2	22.3	5.50	2.21	56.0
SEM	0.42	0.48	0.36	0.32	0.145	0.12	0.16	0.142	0.075	0.32
Wrap type										
OB	46.6	31.4	15.2	24.8	6.03	11.0	22.2	4.83	2.02	57.4
SUN	46.6	31.4	15.2	24.7	6.17	10.9	22.3	4.80	2.07	57.2
SEM	0.30	0.39	0.33	0.23	0.112	0.09	0.12	0.115	0.055	0.23
Contrast ³ ($P > F$)										
(1) Delay vs. control	0.014	0.001	0.278	0.011	0.017	0.005	0.243	0.947	0.895	0.001
(2) Delay: linear	<0.001	<0.001	0.111	0.001	0.001	0.002	0.373	<0.001	0.237	<0.001
(3) Delay: quadratic	0.034	0.689	0.001	0.936	0.476	0.660	0.791	<0.001	0.027	0.291
(4) OB vs. SUN	0.984	0.992	0.989	0.677	0.282	0.713	0.662	0.791	0.538	0.520

¹HEMI, hemicellulose; NDICP, neutral-detergent insoluble CP; ADICP, acid-detergent insoluble CP.

²Concentrations of TDN determined per NRC (2001) using the ADL option to calculate truly digestible fiber.

³Contrasts: (1) delay vs. control, bales wrapped after a 1-, 2-, or 3-d delay vs. those wrapped the same day they were baled; (2) delay: linear, linear effect of wrapping delay; (3) delay: quadratic, quadratic effect of wrapping delay; and (4) OB vs. SUN wrap.

clarity in responses may be related to the relatively short duration of heating before bales were wrapped in polyethylene film.

Poststorage Nutritive Value

Residual concentrations of WSC following silage fermentation were greatest when wrapping was delayed by 1, 2, or 3 d compared with the 0-d positive control (3.3 vs. 2.8%; $P = 0.001$), and increased linearly ($P < 0.001$) with the length of time delay. Generally, the low residual WSC concentrations observed in the 0-d positive control bales on a poststorage basis reflect the greater production of fermentation acids in those silages compared with bales with wrapping delays (Table 6). Concentrations of NDF (48.0 vs. 45.4%; $P < 0.001$), hemicellulose (14.5 vs. 12.4%; $P < 0.001$), and ADL (6.14 vs. 5.81%; $P = 0.005$) were greater for bales with wrapping delays compared with 0-d positive controls; in addition, a strong linear ($P < 0.001$) effect was found on time delay for each response variable. This response could be linked directly to the elevated internal bale temperatures associated with wrapping time delay (Figure 8), yielding a positive linear relationship for NDF ($y = 0.14x^2 + 40.5$; $R^2 = 0.666$; $P < 0.001$). This response for NDF also is consistent with NDF increases in response to spontaneous heating within large-round bales of alfalfa hay (Coblentz and Hoffman, 2009b). Unlike NDF, hemicellulose, and ADL, concentrations of ADF and cellulose were largely static through a 2-d time delay, but increased thereafter, yielding linear ($P = 0.006$) and quadratic ($P = 0.018$) effects for ADF, but only a quadratic ($P = 0.043$) effect for cellulose.

Concentrations of CP declined linearly ($P = 0.007$) with wrapping delay, but the total range across delay treatments was very narrow (22.4 to 22.0%). Residual fiber-associated CP following extraction in neutral or acid detergent was greater ($P < 0.001$) in bales wrapped after 1-, 2-, or 3-d delays, and also increased linearly ($P < 0.001$) with time delay. A quadratic ($P = 0.014$) effect also was detected for NDICP, which was primarily associated with diminishing proportional responses as time delays were extended; this response was not observed for ADICP ($P = 0.437$). As observed for NDF, NDICP and ADICP were associated directly with the internal bale temperature at the time bales were wrapped, yielding quadratic relationships in both cases (Figures 9 and 10, respectively). This response is consistent with the normal relationship between fiber-associated CP and heating within forages and feedstuffs (Licitra et al., 1996), and mirror previous responses within large-round bales of alfalfa-orchardgrass hays (Coblentz et al., 2010). Coefficients of determination for these regressions on heating indicated very close associations between NDICP ($R^2 = 0.835$) or ADICP ($R^2 = 0.698$) and heating in baled silages. Although ADICP increased with heating in silage bales, the percentage of total CP comprised by ADICP ranged between 9.2 and 12.0%, which is within recommended targets for normal silage fermentation (Mahanna and Chase, 2003). Energy density of silages (TDN) was reduced when wrapping was delayed compared with no delay (56.1 vs. 57.3%; $P < 0.001$), and these reductions were explained by both linear ($P < 0.001$) and quadratic ($P = 0.013$) effects of time delay. As observed for fiber-associated CP, changes in TDN with heating for these silages (Fig-

Figure 8. Linear regression of NDF after a 97-d storage period on internal bale temperature at the time alfalfa silage bales were wrapped with polyethylene films containing either an O₂ barrier or no barrier at Marshfield, Wisconsin.

ure 11) was quadratic in nature ($y = -0.0039x^2 + 0.31x + 51.2$; $R^2 = 0.605$; $P < 0.001$).

CONCLUSIONS

Producers often ask about the effects of wrapping delays on silage fermentation and quality. Generally, fermentation was impaired by wrapping delays, especially when wrapping was delayed beyond 24 h, resulting in reduced production of fermentation acids and a less acidic final pH. Within this study, alfalfa silage bales wrapped within 4 h of baling at 59.6% moisture exhibited some evidence of clostridial activity, yielding elevated concentrations of both NH₃-N and butyric acid. Based on these results, a maximum moisture threshold of about 60% is recommended; in addition,

Figure 9. Quadratic regression of neutral-detergent insoluble CP (NDICP) after a 97-d storage period on internal bale temperature at the time alfalfa silage bales were wrapped with polyethylene films containing either an O₂ barrier or no barrier at Marshfield, Wisconsin.

Table 6. Poststorage nutritive value (% of DM) of alfalfa silage bales wrapped in stretch film either with (OB) or without (SUN) an O₂-limiting barrier, and after time delays as long as 3 d

Treatment	WSC ¹	Starch	NDF	ADF	HEMI ¹	Cellulose	ADL	Ash	CP	NDICP ¹	ADICP ¹	TDN ²
Wrapping delay, d												
0	2.8	0.92	45.4	33.0	12.4	26.9	5.81	11.2	22.4	3.25	2.07	57.3
1	3.0	0.61	46.5	33.0	13.4	26.9	5.88	11.3	22.4	4.30	2.20	56.9
2	3.6	0.86	47.9	32.8	15.1	26.5	5.91	11.2	22.1	5.07	2.41	56.5
3	3.3	0.72	49.7	34.7	15.1	27.8	6.62	11.3	22.0	5.46	2.64	54.8
SEM	0.15	0.083	0.40	0.41	0.20	0.35	0.095	0.12	0.19	0.146	0.067	0.29
Wrap type												
OB	3.2	0.74	47.4	33.3	14.1	27.0	6.09	11.3	22.2	4.54	2.32	56.3
SUN	3.1	0.82	47.3	33.4	14.0	27.0	6.02	11.2	22.3	4.50	2.34	56.5
SEM	0.12	0.059	0.28	0.31	0.14	0.28	0.067	0.08	0.17	0.114	0.048	0.22
Contrast ³ ($P > F$)												
(1) Delay vs. control	0.001	0.049	<0.001	0.237	<0.001	0.621	0.005	0.670	0.076	<0.001	<0.001	<0.001
(2) Delay: linear	<0.001	0.323	<0.001	0.006	<0.001	0.088	<0.001	0.911	0.007	<0.001	<0.001	<0.001
(3) Delay: quadratic	0.069	0.314	0.326	0.018	0.014	0.043	0.001	0.836	0.832	0.014	0.437	0.013
(4) OB vs. SUN	0.573	0.321	0.881	0.964	0.705	0.924	0.506	0.526	0.470	0.799	0.764	0.564

¹WSC = water-soluble carbohydrates; HEMI, hemicellulose; NDICP, neutral-detergent insoluble CP; ADICP, acid-detergent insoluble CP.

²Concentrations of TDN determined per NRC (2001) using the ADL option to calculate truly digestible fiber.

³Contrasts: (1) delay vs. control, bales wrapped after a 1-, 2-, or 3-d delay vs. those wrapped the same day they were baled; (2) delay: linear, linear effect of wrapping delay; (3) delay: quadratic, quadratic effect of wrapping delay; and (4) OB vs. SUN wrap.

Figure 10. Quadratic regression of acid-detergent insoluble CP (ADICP) after a 97-d storage period on internal bale temperature at the time alfalfa silage bales were wrapped with polyethylene films containing either an O₂ barrier or no barrier at Marshfield, Wisconsin.

alfalfa forages wrapped in polyethylene film within this moisture range might be better preserved by including a lactic-acid-producing inoculant to aid fermentation, or by further wilting to about 55% moisture. Under the management used in this study, inclusion of an OB within the film wrap had no effect on forage nutritive value or silage fermentation characteristics; however, the wrapping protocol imposed (7 layers) could be considered conservative with respect to excluding air and maintaining a good silage fermentation environment. Additional evaluation will be needed to determine if there are benefits from inclusion of an OB when plastic layers are reduced.

Figure 11. Quadratic regression of TDN after a 97-d storage period on internal bale temperature at the time alfalfa silage bales were wrapped with polyethylene films containing either an O₂ barrier or no barrier at Marshfield, Wisconsin.

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