Harvest and Storage of Two Perennial Grasses as Biomass Feedstocks

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Abstract. *Some perennial grasses, such as reed canarygrass (RCG) and switchgrass (SWG), have prolific yield and low inputs, making them attractive as biomass feedstocks. When harvested as biomass, these grasses are more mature and have much greater yield than when harvested as animal forage. Much is unknown about how harvest equipment performance and storage characteristics are affected by these crop conditions. The objective of this research was to determine the crop yield and drying rate, baling rate, bale density, and bale storage characteristics of these grasses harvested as biomass feedstocks. After the establishment year, the three-year average yield of RCG was 21% less than SWG (7.70 vs. 9.69 Mg DM ha^{-1}) using a single-cutting system that occurred in August. When the crops were left standing over winter and harvested in the spring, DM yields were reduced by 17% and 26% for SWG and RCG, respectively. When crop yield was similar, switchgrass tended to dry faster than reed canarygrass. Drying rates of these grasses were faster than typically experienced with forage crops like alfalfa. Bale density averaged 163 kg DM m^{-3} with no significant differences between crops or type of wrap (twine or net). Dry bales stored outdoors for 9 to 11 months averaged 3.8%, 4.8%, 7.5%, 8.7%, and 14.9% DM loss for bales wrapped with plastic film, breathable film, net wrap, plastic twine, and sisal twine, respectively. Bales stored under cover averaged 3.0% DM loss. The chemical and physical properties of bales stored outdoors were spatially variable. Preservation by ensiling in a tube produced average DM losses of 1.1% at average moisture of 39.9% (w.b.).*

Keywords. Biomass, Biomass collection, Biomass harvest, Density, Grasses, Losses, Reed canarygrass, Silage, Switchgrass.

I n North America, the main feedstock for fuel ethanol is currently corn grain. New enzyme hydrolysis and fermentation technologies are being developed to produce ethanol from cellulosic biomass such as grasses, straw, and wood. The energy balance for these materials has the potential to be much more favorable than with corn grain (Farrell et al., 2006). Often mentioned as a biomass feedstock is switchgrass (*Panicum virgatum* L.), which is a warm-season (C4) perennial grass. Switchgrass (SWG) is a coarse-stemmed plant that grows 1 to 2 m tall with yields between 8 and 20 t DM ha^{-1} (Huisman, 2003). SWG is established by seed, has a low nutrient demand, efficient water use, and good persistence. Another potential perennial grass that could serve as a biomass feedstock is reed canarygrass (*Phalaris arundinacea* L.). Reed canarygrass (RCG) is a cool-season (C3) grass adapted to much of the northern half of North America, so it may be better suited as a biomass crop than SWG in northern climates. Although RCG is considered lower yielding of the most important biomass grasses, it is a key perennial, rhizomatous grass that can be produced in regions with short vegetation periods and cold winters, and it is especially well suited to poorly drained soils (Lewandowski et al., 2003). It begins growth in early spring, with growth peaking in mid-June and declining in mid-August. Although there has been much research concerning agronomic practices related to these species, there has not been a great deal of work related to harvest, field drying, packaging, and storing of these crops when considered as biomass feedstocks.

One production variable that needs to be considered with perennial grasses to be used as biomass feedstocks is cutting frequency. Since high forage quality for livestock production is not required, it may be more economical to harvest perennial grasses once per year. Wright (1990) reported that SWG and RCG cut twice per year produced a 47% and 31% greater DM yield, respectively, than a single-cutting system. In Oklahoma, harvest frequency was the most important factor affecting SWG yields over a two-year study, with average DM yields of 16.3, 14.7, and 12.9 Mg ha^{-1} year^{-1} for three, two, and single cuttings per year, respectively (Thomason et al., 2004). An upland SWG cultivar produced 36% more with two cuttings rather than one in the southeast U.S. (Fike et al., 2006). Two SWG harvests per year may increase yields in some cultivars, but a single annual harvest maximizes yields in other cases (Parrish and Fike, 2005). If more than two harvests are taken, then additional N may need to be applied to compensate for the N removed in the late-season harvest. Taking more than two harvests per year often adversely affects long-term productivity and persistence (Parrish and

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Fike, 2005). In Sweden, reed canarygrass yield decreased with more than two cuttings per year (Geber, 2002).

Estimating costs for biomass feedstock logistics requires data concerning baling productivity and bale density. Perennial grasses cut once or twice per year have yields much greater than those typically experienced with forage crops, so conventional hay harvesting equipment may not adequately handle the crop volume, reducing baling productivity. Bransby et al. (1996) reported that average SWG bale density was 136 kg DM m^{-3}, and bale density was not dependent upon yield. Baling productivity for a Class IV round baler (ISO, 1999) was 9.2 Mg DM h^{-1} in their study. The type of wrap used was not identified.

Another important aspect of the production system for perennial grasses is the physical and chemical condition of the grasses after a period of conservation. DM losses of SWG in round bales stored outside on crushed rock were 2% to 4% of DM over an 8.5-month period in Indiana (Johnson et al., 1995). Twine-wrapped bales stored outside on the ground lost up to 15% of DM during this period. DM losses of SWG ranged from 5% to 13% for bales stored outdoors over 12 months in Pennsylvania (Sanderson et al., 1997). SWG bales exposed to 650 mm of precipitation showed a significant loss of extractives in both the outer layer (11%) and the core (8%) of the bale (Wiselogel et al., 1996).

The objectives of this research were to establish plots of SWG and RCG in a northern U.S. location and compare yields as a function of cutting frequency and date; to collect production data relative to crop drying rate, baling rate, and bale density; and to investigate storage losses and chemical compositional changes in these crops using a variety of round bale storage schemes.

MATERIALS AND METHODS

Both RCG and SWG plots were established in the spring of 2004. Granular urea (46-0-0) was top dressed at the rate of 90 kg N ha^{-1} in April of each year of the study for both grasses. Crop yield, baling productivity, bale density, field drying rate, and bale storage characteristics were quantified during 2005-2008. However, the two crops were used for other research purposes, so it was not possible to quantify all parameters at every harvest because of insufficient plot area and yield (table 1).

YIELD, BALING PRODUCTIVITY, AND BALE DENSITY

With biomass crops, high yields take priority over nutrient composition, so one way to reduce costs is to harvest only once or twice per year. SWG is a warm-season grass, so it was cut only once per year because minimal re-growth would be expected in the northern climate where this study was conducted. Of interest is whether cutting should take place in late summer or late fall, so these two cutting schemes were used (table 1). Some yield loss would be expected by a late fall cutting due to translocation of carbohydrates and nutrients into the root system. RCG is a cool-season grass, so a robust late-summer/early-fall re-growth can be expected. Two cutting schemes were considered with RCG: a single cutting in the late summer or two-cuttings, one in mid-summer and another in late fall. In 2007 and 2008, part of each crop was allowed to over-winter and was harvested as soon as field conditions allowed in the spring.

Table 1. Cutting date and frequency, grass type used, and parameters quantified during 2005-2008.[a]

Year, Cutting Frequency, and Cutting Date	Yield	Baling Productivity	Field Drying Rate	Bale Storage
2004: Establishment year				
	RCG, SWG	--	RCG, SWG	--
2005: Single cutting[b]				
27 October	RCG, SWG	--	--	--
30 August	RCG, SWG	RCG, SWG	RCG, SWG	RCG, SWG
2005: Two cuttings[c]				
27 October	RCG	--	--	--
14 July	RCG	RCG	RCG	RCG
2006: Single cutting[b]				
1 November	RCG, SWG	--	--	--
29 August	RCG, SWG	--	--	--
14 August	RCG, SWG	RCG, SWG	RCG, SWG	--
2006: Two cuttings[c]				
1 November	RCG	--	--	--
18 July	RCG	RCG	--	RCG
2007: Single cutting[b]				
30 October	RCG, SWG	--	--	--
31 August	RCG, SWG	--	--	--
21 April[d]	RCG, SWG	--	--	--
2007: Two cuttings[c]				
30 October	RCG	--	--	--
25 July	RCG	--	--	--
2008: Single cutting[b]				
11 November	RCG, SWG	--	--	--
8 April[e]	RCG, SWG	--	--	--

[a] RCG = reed canarygrass; SWG = switchgrass.
[b] Crop cut once per year on one of the reported dates.
[c] Crop cut twice per year: first cutting taken on earlier date, second cutting of re-growth cut on later date.
[d] Crop grown during 2007 growing season but harvested in 2008 after over-wintering in the field.
[e] Crop grown during 2008 growing season but harvested in 2009 after over-wintering in the field.

When the crop was cut for drying or storage studies, it was baled in large round bales, and the mass and area harvested in each bale was used to estimate crop yield (table 1). Bales were formed by an experienced round bale operator with a John Deere model 567 round baler (LRB 157 cm width × 160 cm diameter). The baler was operated as fast as possible without plugging the pick-up, and the belt tension was set to maximum. The variable density core option was not activated, so belt tension was the same throughout bale formation. On 14 August 2006, a Case IH model LBX331 large square baler (LSB) was used to compare baling productivity and bale density with the LRB.

Baling productivity was defined as the total time required from start of bale formation of one bale until the start of the next bale. Round bales were wrapped either using 8 cm twine spacing plus six end wraps or 2.5 layers of mesh net wrap. The bale monitor/controller automatically started the wrapping sequence after the desired bale diameter had been reached and controlled the entire wrapping process. The baler was equipped with a bale ejector, so no backing was required. The center-to-center distance between adjacent swaths was measured at multiple locations to quantify average width harvested. Only single windrows were baled because of the high yields.

The distance between each bale was measured with a land wheel to the nearest 0.5 m, allowing calculation of baling speed and crop yield. The vertical and horizontal diameter on both sides of all bales was measured to the nearest 1 cm to allow calculation of bale volume. Each bale was weighed to the nearest 0.5 kg on a 1,800 kg capacity platform scale. The bales were then radially bored twice from either side to a depth of roughly 50 cm using a 5 cm diameter boring tube. The bore samples were combined, mixed, and then split into four subsamples. Two subsamples were used for moisture determination and were oven dried at 103°C for 24 h. The other two samples reserved for chemical compositional analysis (from bales used for storage studies only) and were oven dried at 65°C for 72 h (*ASABE Standards*, 2008).

DRYING RATE

The crop was cut and conditioned with a John Deere model 4990 disk cutterbar windrower (4.5 m cut width) equipped with urethane conditioning rolls. The first three trials (table 1) compared the drying rate of three different swath widths: approximately 30%, 60%, or 100% of cut width. The latter treatment was achieved by tedding immediately after cutting. In the final two trials (table 1), two conditioning treatments were compared: roll and impeller, both placed in swaths 60% of cut width. The impeller treatment was created by using the same cutting platform described above but equipped with an impeller conditioner operating at 870 rpm. In all cases, four replicate swaths per treatment were used.

A single sample of material was collected from each replicate swath right after cutting and periodically during the daylight hours during the next few days. For each replicate sample, about 0.5 m of material was collected across the full width and depth of the swath and then size-reduced by chopping in a lab-scale precision-cut chopper. The chopped material was mixed, and then three subsamples were collected and oven dried for 24 h at 103°C per ASABE Standard S358.2 (*ASABE Standards*, 2008).

The drying data were analyzed assuming that the data fit the following exponential drying rate model (Rotz and Chen, 1985):

$$\frac{M}{M_0} = e^{-kt} \tag{1}$$

where

M = dry basis moisture at the end of the time interval
M_0 = dry basis moisture at the beginning of the time interval
k = drying constant (h^{-1})
t = length of time interval (h).

For each day and treatment, the drying constant was then transformed based on the least square linear regression model of several data points (Greenlees et al., 2000):

$$k = \frac{n \sum t_i \ln \mu_i - (\sum t_i) \sum \ln \mu_i}{n \sum t_i^2 - (\sum t_i)^2} \tag{2}$$

where

k = transformed drying rate constant (h^{-1})
n = number of observations in each day
t_i = actual drying time between each observation (h)
μ_i = dry basis moisture content.

A daily transformed k value was calculated for each treatment, and an average drying constant was also determined over the entire period. A two-way analysis of variance was used to block confounding effects of different days when analyzing the data across multiple days. Statistical differences were based on a least significant difference (LSD) with a probability of 95% (Steel et al., 1996).

STORAGE CHARACTERISTICS

Eight treatments were considered in the storage study. Five treatments involved outdoor storage of dry bales wrapped with sisal twine (ST), plastic twine (PT), or mesh net wrap (NW), or wrapped circumferentially with either three layers of 1 mil plastic film (PF) or with a breathable non-woven film (BF) similar to the vapor barrier used in home construction. These bales were placed directly on grass sod with the bales spaced about 20 cm apart in the row. Rows of bales were spaced about 2 m apart on a gentle slope in lines running roughly east to west. The sixth treatment used a pyramid of 18 net-wrapped bales stored outdoors but under a typical bale tarp (BT). The seventh treatment used net-wrapped bales stored indoors in a completely enclosed shed (IN). The eighth treatment used net-wrapped bales formed at higher moisture (~35% w.b.) and film-wrapped in a tube (see procedure below). In all cases, except for the tarped bales, five replicate bales were formed per treatment. Three separate trials were conducted, although yield was not always sufficient to allow all treatments to be included in each trial (table 2). Before the bales were placed into storage, bale weight, volume, and moisture were determined using the procedures described above. When the bales were removed from storage, the width, height, and diagonal diameters were measured to the nearest 1 cm. Bales were then weighed as previously described.

To achieve a relative estimation of spatial moisture distribution, a Delmhorst model F-2000 conductance moisture sensor was inserted to a depth of 25 cm on the ends of the bale roughly parallel to its longitudinal axis. Measurements were taken at 5, 10, 15, 20, 30, and 50 cm radial distance from the bale surface and also at the center of the bale. Measurements were taken at the two horizontal and two vertical radii on one side of the bale and at the radii offset approximately 45° from these on the other side. Matlab R2006a was then used to develop spatial moisture distributions using these 50 data points.

Table 2. Treatments, storage period, and accumulated precipitation during study of storage characteristics of RCG and SWG bales.[a]

Crop[a]	Treatments[b]	Stored	Removed	Days in Storage	Accum. Precip. (mm)[c]
RCG	ST, PT, NW, BF, IN, WE	15 July 2005	14 June 2006	334	718
RCG, SWG	ST, PT, NW, BF, PF, IN, WE	30 Aug. 2005	19 June 2006	293	568
RCG	PT, NW, BF, PF, BT, IN	18 July 2006	25 May 2007	311	655

[a] RCG = reed canarygrass; SWG = switchgrass.
[b] ST = sisal twine, PT = plastic twine, NW = net wrap, BF = breathable film, PF = plastic film, IN = stored indoors, BT = under bale tarp, and WE = wrapped in tube of plastic film and ensiled.
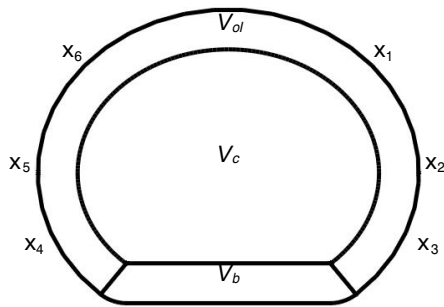[c] Accumulated precipitation during the storage period.

Figure 1. Locations of the volume of the outer layer (V_{ol}), core (V_c), and base (V_b) of the bale used to calculate the volume-adjusted bale moisture for bales removed from storage. Also shown are the six angular positions (X_1 to X_6) on the bale where bore samples were taken to determine the moisture of the outer layer.

If a portion of the bale was left on the ground when it was lifted, this material was collected, weighed, and two subsamples collected to determine oven dry moisture. This material was considered unrecoverable and was included in the DM loss. After the bale had been lifted, the length in contact with the soil was measured to the nearest 1 cm at three locations. Six bore samples of 5 cm diameter were then taken to a depth of 20 cm (outer layer, fig. 1). Samples were taken at the 1:30, 3:00, 4:30, 7:30, 9:00, and 10:30 clock positions (X_1 to X_6, respectively, fig. 1). On two of the replicate bales, the samples from the X_1, X_2, and X_4 positions were used for moisture determination, and the remaining locations used for chemical analysis. The opposite allocations were used for the remaining three replicates. Two additional bore samples from the core of the bale, one each at the X_2 and X_5 positions, were taken from a depth of 20 to 50 cm. These bore samples were each split into two subsamples, one each for moisture and chemical analysis. The bale was then tipped on end and four bore samples were taken from the bottom of the bale to a depth of 20 cm. Two bore samples were used for moisture determination and two for chemical analysis. All moisture samples were oven dried at 103°C for 24 h.

Bore sampling procedures for the ensiled bales involved taking six bore samples to a depth of 50 cm, two each at the 3:00, 6:00, and 9:00 clock positions. An additional two bore samples were taken from a depth of 20 to 50 cm at the 3:00 and 9:00 clock positions. Both bore samples at each location were combined, mixed, and then split into three subsamples. Two subsamples were oven dried at 65°C for 72 h for moisture determination and subsequent chemical analysis. The remaining subsamples were combined and frozen for subsequent analysis of fermentation products.

All samples for chemical composition analysis were oven dried at 65°C for 72 h and then analyzed by the USDA-ARS U.S. Dairy Forage Research Center for crude protein (CP) (using a Leco FP-2000A nitrogen analyzer, Leco Corp., St. Joseph, Mich.), acid detergent fiber (ADF), neutral detergent fiber (NDF), acid detergent lignin (ADL), and ash using wet laboratory techniques (Hintz et al., 1995). Ensiled samples were analyzed at the USDA-ARS U.S. Dairy Forage Research Center for pH and common fermentation products using high-performance liquid chromatography (Muck and Dickerson, 1988).

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

$$M_a = \frac{(M_{ol} \cdot V_{ol} + M_c \cdot V_c + M_b \cdot V_b)}{V_t} \quad (3)$$

where
M	= wet basis moisture content
V	= volume of bale section
ol, c, b, t, a	= outer layer (ol), core (c), bottom (b), total (t), and volume-adjusted total (a), respectively.

RESULTS
YIELD

After the establishment year, the three-year average yield of RCG was 21% less than SWG (7.70 vs. 9.69 Mg DM ha^{-1}) using a single-cutting system that was employed in August (table 3). Plot-scale yields of the same variety of SWG averaged 11.44 Mg DM ha^{-1} at the same site (Casler et al., 2004).

Table 3. Yield of RCG and SWG as quantified by weight, moisture, and area required per bale.[a]

Year, Cutting Frequency, and Cutting Date	Yield (Mg DM ha^{-1})		Accumulated Precipitation (mm)[b]
	RCG	SWG	
2004: Establishment year			
9 October[c]	3.50	5.06	184
2005: Single cutting			
30 August	8.28	8.96	264
27 October	--	8.71	375
2005: Two cuttings			
14 July	6.28	--	105
27 October	3.04[d]	--	270[e]
2006: Single cutting			
14 August	7.77	9.23	326
29 August	8.06	10.50	442
1 November	--	9.03	619
2006: Two cuttings			
18 July	7.96	--	260
1 November	2.42[d]	--	359[e]
2007: Single cutting			
31 August	7.07	10.88	523
30 October	--	9.99	667
21 April	5.53[f]	7.94[f]	300[g]
2007: Two cuttings			
25 July	7.41	--	188
30 October	2.66[d]	--	479[e]
2008: Single cutting			
11 November	7.85	9.62	646
8 April[e]	5.44[h]	8.24[h]	211[i]

[a] RCG = reed canarygrass; SWG = switchgrass.
[b] Unless noted otherwise, accumulated precipitation from 1 May until cutting.
[c] Yield after initial growth of biomass had been removed on 29 June (RCG) and 12 July (SWG).
[d] Re-growth from crop cut 14 July 2005, 18 July 2006, and 25 July 2007, respectively.
[e] Accumulated precipitation during re-growth period.
[f] Crop grown during 2007 growing season but harvested after over-wintering in the field.
[g] Additional accumulated precipitation from 1 November 2007 to 21 April 2008.
[h] Crop grown during 2008 growing season but harvested after over-wintering in the field.
[i] Additional accumulated precipitation from 12 November 2008 to 8 April 2009.

A late-August cutting, which was preferred by producers in Nebraska, South Dakota, and North Dakota participating in an SWG field-scale demonstration project, produced three-year average yields of 6.6 Mg DM ha^{-1} across nine trials (Schmer et al., 2008). Yields of RCG averaged 9.0 Mg DM ha^{-1} over an eight-year study in Sweden (Lewandowski et al., 2003). A single cutting of RCG in late summer reduced yield by 2% to 5% compared to a mid-summer cutting (2006 and 2007), except in 2005 when rainfall was low early in the growing season. Harvesting switchgrass in the late fall resulted in a loss of 1% to 14% of DM compared to a late-summer harvest. The two-cutting RCG system produced only 7% greater yield than a single cutting of SWG but 24% greater yield than a single cutting of RCG.

When the crops were left standing over-winter and harvested in the spring, DM yields were reduced by 17% and 26% for SWG and RCG, respectively. Mid- to late April was the soonest the ground was firm enough to support wheel traffic without field damage. Although harvest was quite late in the spring, it was possible to bale directly behind the cutting equipment because average moisture content was less than 11% (w.b.) for all bales made in 2008 and 2009. Yields of RCG in Sweden were reduced by 17% when harvest took place in the spring rather than late fall (Lewandowski et al., 2003). Adler et al. (2006) reported yield reductions of 27% over a three-year period when SWG was harvested in the spring. Adler et al. (2006) attributed the yield reduction to the inability of the harvesting equipment to capture all the potential DM. However, we observed that the amount of DM left by the windrower was similar to that experienced at late-fall harvest, so yield reduction could not entirely be attributed to the harvest equipment. It was observed that the plants had senesced, and the many of the leaves had self-pruned. By the time harvest had occurred in April, the fallen leaves had decomposed, making their harvest impossible.

DRYING RATE

Weather conditions during the four drying studies were considered good for the time of year (table 4), with no precipitation during field wilting. Like perennial forage crops (Shinners and Herzmann, 2006; Shinners et al., 2006), RCG and SWG dried more quickly when they were placed in a wide swath (table 5). In August 2005, when yield was relatively similar between the two grasses (table 3), there were no significant differences in drying rate between the two crops. In August 2006, RCG had a significantly faster drying

Table 4. Average ambient conditions during the daytime drying period when samples were collected for the five different drying rate experiments conducted.

Date	Ambient Temp. (°C)	Solar Insolation (W m^{-2})	Wind Speed (m s^{-1})	Relative Humidity (%)
2004				
9 October	18	491	4.3	36
10 October	16	495	2.4	50
11 October	14	432	2.6	58
2005				
14 July	30	548	4.0	50
15 July	29	718	2.6	46
29 August	26	615	3.2	53
30 August	21	456	4.0	72
31 August	22	587	2.9	61
2006				
18 July	26	657	3.1	51
14 August	24	556	6.0	50
15 August	23	645	3.4	50

rate than the SWG, which might be partially explained by the 16% lower yield for the reed canarygrass (table 3). There was no significant difference in drying rate between conditioner treatments (table 5).

The drying rate constants reported here are greater than those reported for alfalfa or grass crops (Rotz, 1995; Greenlees et al., 2000; Shinners and Herzmann, 2006; Shinners et al., 2006) despite the fact that the grasses had yields over twice that of typical forages (table 3). There were several observed differences between these biomass crops and typical forage crops. First, the average moisture at cutting was 54% and 64% (w.b.) for RCG and SWG, respectively, which is considerably drier than typical forage crops at cutting. These grasses were very mature at cutting, with large, stiff stems over 1.5 m long. The swaths were observed to have a well-formed structure, which apparently allowed good air movement through the swath. Perennial forage grasses and legumes often slump into the stubble right after cutting due to their high moisture and the suppleness of their stems. This phenomenon was not observed with these low-moisture, stiff-stemmed biomass grasses. These mature crops also had very large leaf surface area, which also promoted rapid drying. In all cases studied, the crop was below 20% (w.b.) moisture in the afternoon of the day after cutting, and in some cases reached baling moisture in a single day of wilting (figs. 2 to 4).

Table 5. Average drying rate coefficients (h^{-1}) over the entire drying period for RCG and SWG.[a]

	RCG			SWG			
Date	100% Swath Width[b]	60% Swath Width[b]	30% Swath Width[b]	100% Swath Width[b]	60% Swath Width[b]	30% Swath Width[b]	LSD[c] (p = 0.05)
9-11 October 2004	--	0.229 d	0.183 c	--	0.157 b	0.116 a	0.020
14-15 July 2005	0.235 b	0.207 ab	0.194 a	--	--	--	0.025
29-31 August 2005	0.177 cd	0.138 abc	0.101 a	0.195 d	0.154 bcd	0.118 ab	0.041
	Roll Conditioner[d]	Impeller Conditioner[d]		Roll Conditioner[d]	Impeller Conditioner[d]		
18 July 2006	0.176	0.153		--	--		0.031
14-15 August 2006	0.171 c	0.162 bc		0.142 ab	0.131 a		0.028

[a] RCG = reed canarygrass; SWG = switchgrass.
[b] Width of the swath as an approximate fraction of the cut width (4.5 m).
[c] Averages in the same row followed by different letters are significantly different at 95% confidence.
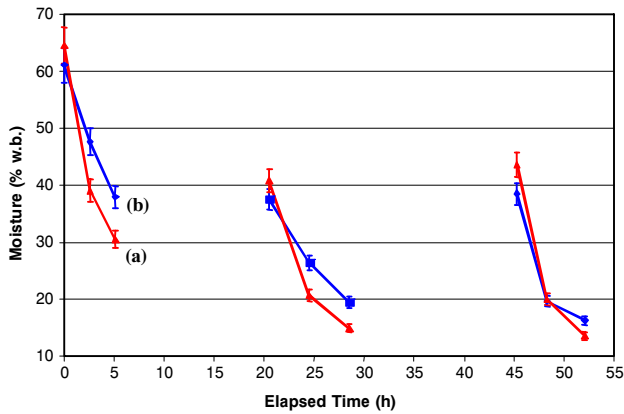[d] Width of swaths was approximately 60% of cut width (4.5m).

Figure 2. Drying rate of (a) RCG and (b) SWG cut on 9 October 2004 at 11:30 a.m. and placed in swaths approximately 60% of cut width.
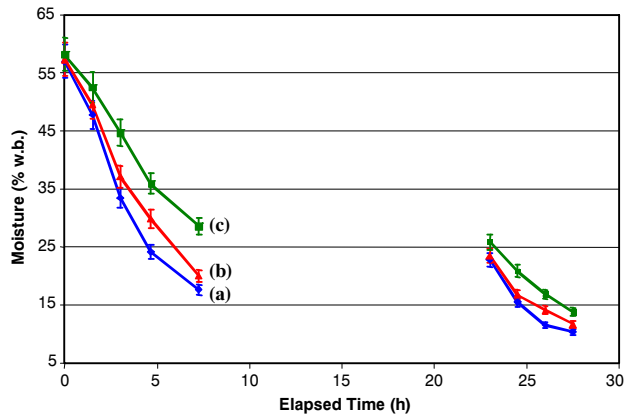

Figure 3. Drying rate of RCG cut on 14 July 2005 at 10:00 a.m. and placed in swaths approximately (a) 100%, (b) 60%, and (c) 30% of cut width.
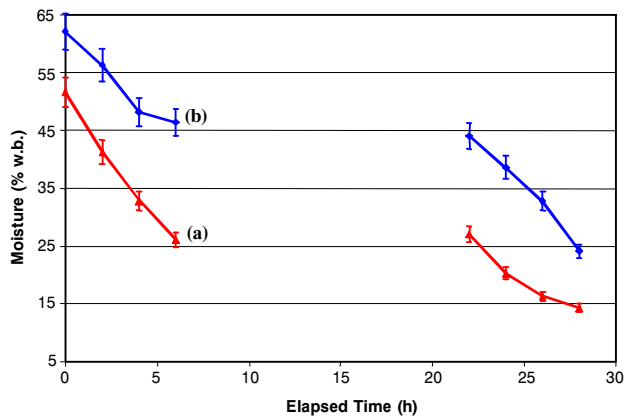

Figure 4. Drying rate of (a) RCG and (b) SWG cut on 14 August 2006 at 11:00 a.m., conditioned with a roll conditioner, and placed in swaths approximately 100% of cut width.

Table 6. Crop moisture, bale density, and baling productivity for RCG and SWG baled with two types of bale wrap for LRB (net or twine) or two baler types.[a]

Date, Grass Type, Baler Type, and LRB Wrap Type	Moisture (% w.b.)		Bale Density (kg DM m^{-3})	Baling Productivity (Mg DM h^{-1})
	At Cutting	At Baling		
14 July 2005				
RCG				
LRB - Net	55.7	11.4	152	--
LRB - Twine	55.7	11.3	154	--
LSD[b] (p = 0.05)		1.7	4	
30 August 2005				
RCG				
LRB - Net	52.4	15.1 a	168 ab	13.4 b
LRB - Twine	52.4	15.2 a	171 b	8.3 a
SWG				
LRB - Net	66.2	22.6 b	165 a	17.7 c
LRB - Twine	66.2	22.3 b	166 a	13.5 b
LSD[b] (p = 0.05)		2.5	3	1.8
18 July 2006				
RCG				
LRB - Net	56.4	16.3	148	20.5 b
LRB - Twine	56.4	20.2	147	16.6 a
LSD[b] (p = 0.05)		5.1	7	3.7
14 August 2006				
RCG				
LRB - Net	51.7	11.9 a	140 a	17.0 a
LSB	51.7	11.1 a	197 c	21.6 b
SWG				
LRB - Net	62.2	15.0 ab	142 a	20.3 b
LSB	62.2	16.9 b	186 b	25.2 c
LSD[b] (p = 0.05)		3.5	9	2.6

[a] RCG = reed canarygrass, SWG = switchgrass, LRB = large round baler, and LSB = large square baler.

[b] Averages in the same column followed by different letters are significantly different at 95% confidence.

ferences were found with alfalfa and alfalfa/grass bales (Shinners et al., 2009b). Productivity ranged from 8.3 to 13.5 kg DM h^{-1} and from 13.5 to 17.7 kg DM h^{-1} for twine and net wrap, respectively (table 6). Alfalfa baling productivity with the same model baler was 11.6 and 15.3 kg DM h^{-1} for twine and net wrap, respectively (Shinners et al., 2009b). Ground speed was limited with RCG and SWG because the physical volume of the raked windrow overwhelmed the open area of the baler pick-up, causing crop to pile up in front of the pick-up at higher speeds. Forage crops for animal use are typically cut three to four times per growing season to produce acceptable feed quality. This cutting frequency produces yields much lower than those that were experienced with biomass crops cut only once or twice per growing season. Future modifications to the baler pick-up and throat may be needed to handle the high yield and physical volume of crops for biomass feedstocks. Baling productivity was greater for SWG than RCG (table 6). It was observed that the volume of the windrows was greater for RCG than for SWG, which meant that the ground speed had to be less for the former crop to prevent crop piling up ahead of the pick-up.

Bale density was not affected by type of wrap or crop (table 6). Density of alfalfa and alfalfa/grass bales averaged 174 kg DM m^{-3} over four cuttings (Shinners et al., 2009b), which was similar to those found with RCG and SWG. Truck weight and volume legal restrictions limit bale density to

BALING PRODUCTIVITY AND BALE DENSITY

Compared to wrapping with twine, wrapping with net increased baling productivity by 31% to 61% for RCG and SWG, respectively (table 6) because the time to wrap with twine was three to four times greater than with net wrap. Net wrap covered the entire width of the bale at once, while the twine had to be spiral wound around the bale, which resulted in the bale being turned about 4 and 25 revolutions during net and twine wrapping, respectively. Similar productivity dif-

Table 7. Moisture distribution, aggregate bale moisture, and DM loss for dry large-round bales of RCG stored on 14 July 2005 and removed on 14 June 2006 after 334 days in storage.[a]

Storage Location and Treatment[b]	Moisture (% w.b.)					DM Loss (% of total)
	Into Storage	Removed from Storage			Volume-Adjusted Bale Aggregate	
		Outer Layer	Core	Base		
Outdoor						
ST	11.3 a	21.7 c	14.3 a	59.5 d	25.1 d	14.9 d
PT	11.3 a	23.2 c	15.1 a	36.2 b	20.1 c	7.5 c
NW	11.6 a	20.5 bc	16.2 b	46.0 c	20.6 c	7.7 c
BF	10.7 a	15.4 a	14.8 a	46.1 c	17.8 b	3.0 b
Under cover						
IN	11.6 a	16.6 ab	15.1 a	14.7 a	15.7 a	2.6 ab
WE	33.9 b	33.9 d	34.0 c	38.4 b	34.4 e	0.3 a
LSD[c] (p = 0.05)	0.9	3.9	1.0	3.5	1.7	1.3

[a] RCG = reed canarygrass.

[b] ST = sisal twine, PT = plastic twine, NW = net wrap, IN = stored indoors, BF = breathable film, and WE = wrapped plastic film tube and ensiled.

[c] Averages in the same column followed by different letters are significantly different at 95% confidence.

Table 8. Moisture distribution, aggregate bale moisture, and DM loss for RCG and SWG stored on 30 August 2005 and removed on 19 June 2006 after 293 days in storage.[a]

	Storage Location and Treatment[b]	Moisture (% w.b.)					DM Loss (% of total)
		Into Storage	Removed from Storage			Volume-Adjusted Bale Aggregate	
			Outer Layer	Core	Base		
RCG	Outdoor						
	ST	15.3 ab	24.5 d	15.7 bc	64.4 d	24.4 d	14.5 c
	PT	15.0 a	23.7 d	15.1 b	38.0 b	20.7 c	8.1 b
	NW	17.3 b	20.2 c	15.3 bc	38.6 b	19.4 c	6.5 b
	BF	13.9 a	17.2 ab	16.2 c	39.1 b	16.9 b	5.2 b
	PF	14.2 a	19.3 bc	15.2 b	52.2 c	20.1 c	1.1 a
	Under cover						
	IN	15.0 a	14.8 a	13.4 a	15.6 a	14.1 a	1.6 a
	WE	36.8 c	36.9 e	37.6 d	39.4 b	37.5 e	0.8 a
	LSD[c] (p = 0.05)	2.0	2.7	0.9	6.0	1.5	3.0
SWG	Outdoor						
	ST	23.7 a	22.6 c	15.5 b	63.3 d	22.9 d	15.4 d
	PT	21.0 a	20.1 bc	14.9 ab	29.1 b	18.1 b	9.3 c
	NW	21.8 a	17.5 ab	15.4 b	32.2 b	17.6 b	9.0 c
	BF	23.1 a	15.3 a	14.7 ab	34.2 b	16.7 b	5.4 b
	PF	21.3 a	20.2	14.8 ab	53.6 c	20.4 c	5.7 b
	Under cover						
	IN	24.7 a	15.2 a	14.0 a	19.3 a	14.9 a	4.9 b
	WE	49.0 b	47.1 d	47.3 c	52.8 c	49.5 e	2.0 a
	LSD[c] (p = 0.05)	4.4	3.7	0.9	6.8	1.7	2.6

[a] RCG = reed canarygrass; SWG = switchgrass.

[b] ST = sisal twine, PT = plastic twine, NW = net wrap, IN = stored indoors, BF = breathable film, PF = plastic film, and WE = wrapped plastic film tube and ensiled.

[c] Averages in the same column followed by different letters are significantly different at 95% confidence.

about 210 kg DM m⁻³, depending on bale moisture, bale size, and local road regulations. The bale density of perennial biomass grasses needs to be increased by 20% to 35% to minimize shipping cost.

DRY BALE STORAGE

Precipitation during the three storage periods was 702, 535, and 655 mm, respectively (table 2) (15-year average: 690 mm). When stored on the ground, ST bales had greater DM loss than other treatments, primarily because the twine rotted and the bale lost structure (tables 7 and 8). The lack of twine restraint caused a greater fraction of the bale to be in contact with the ground and significantly increased the mois-

ture in the bottom of the bale (table 7 and 8). ST bales were the only bales where material was left on the ground when it was lifted. This material was considered unrecoverable and was included in the DM loss.

Previous research had shown that NW bales of alfalfa averaged 4.0 percentage units less DM loss than those wrapped in PT (Shinners et al., 2009b). In that study, NW bales had lower moisture in the outer layer and core than PT bales. In this research, moisture in the outer layer and core were generally statistically similar for the two treatments, and these two fractions of the bale made up roughly 35% and 55%, respectively, of the total bale volume. Aggregate bale moisture was similar for PT and NW bales in all trials (tables 7 to 9). The

**Table 9. Moisture distribution, aggregate bale moisture, and DM loss for RCG bales
stored on 18 July 2006 and removed on 25 May 2007 after 311 days in storage.[a]**

Storage Location and Treatment[b]	Moisture (% w.b.)					DM Loss (% of total)
	Into Storage	Removed from Storage				
		Outer Layer	Core	Base	Volume-Adjusted Bale Aggregate	
Outdoor						
PT	16.7	18.7 c	17.2 b	62.2 b	25.2 bc	9.8 d
NW	17.4	16.5 b	17.4 b	63.1 bc	25.1 bc	6.9 c
BF	15.1	17.0 b	16.5 b	63.9 bc	24.6 b	5.6 bc
PF	14.9	19.6 c	16.8 b	65.3 c	25.8 c	4.6 b
Under cover						
BT	17.1	13.7 a	15.5 a	15.5 a	15.0 a	3.3 a
IN	15.4	13.7 a	14.4 a	14.4 a	14.1 a	2.4 a
LSD[c] (p = 0.05)	4.1	1.2	1.1	2.7	1.0	2.1

[a] RCG = reed canarygrass.
[b] PT = plastic twine, NW = net wrap, BF = breathable film, PF = plastic film, BT = under bale tarp, and IN = stored indoors.
[c] Averages in the same column followed by different letters are significantly different at 95% confidence.

biomass grasses were very mature when baled, and both had large-diameter stems. These large stems did not produce a good thatch no matter the type of wrap, so water infiltration during precipitation may have been similar for these wrap types. Although soluble components would have made up a smaller fraction of the total DM in these very mature biomass crops, higher moisture in the outer layer would have contributed to greater biological activity despite potentially lower DM losses due to leaching. Across all trials, DM losses averaged 7.5%, 8.6%, and 14.9% of DM for NW, PT, and ST bales, respectively. In a similar study involving alfalfa hay bales, DM losses averaged 7.3%, 11.3%, and 19.5% of DM for NW, PT, and ST bales, respectively (Shinners et al., 2009b).

Storing bales indoors significantly reduced DM loss compared to all other treatments (tables 7 to 9). The moisture content in the outer layer and base of IN bales was generally significantly less than the ST, PT, or NW treatments, which contributed to the lower DM loss. The magnitude of losses of DM for bales wrapped with BF generally were between IN and NW (tables 7 to 9). The average moisture in the outer layer for the BF bales was 16.2% (w.b.), possibly showing that the film helped keep water out of the bale. However, moisture in the base (~15% of bale volume) of the BF bales ranged from 34.2% to 63.9% (w.b.), which contributed to the higher DM loss compared to storing indoors. Losses of DM were similar between the PF and IN bales (tables 8 and 9). The PF bales had higher moisture in the outer layer and base than the IN bales. Moisture within the PF bales at harvest condensed on the inside surface of the film and eventually drained to the base of the bale. However, the PF prevented rain from reaching the bale and leaching soluble components, which likely lowered potential DM loss compared to other treatments. It was observed that there were patches of green algae on the outside of many of the PF bales.

In the one study that involved both RCG and SWG, losses from SWG bales were greater than from RCG bales, most likely because the latter averaged 22.5% moisture at baling, compared to 15.2% for the former (table 8). These differences were particularly evident with the bales stored indoors, showing the importance of baling as dry as possible to reduce biological activity.

In dry hay bales, the quantities of cell wall polysaccharides (cellulose and hemicellulose) are not typically changed during storage because they are surrounded by the lignin matrix. Lignin appears to act as a physical barrier to most microbial enzymes that might degrade the cell wall polysaccharides (Jung and Deetz, 1993). Cellulose concentrations changed during storage of dry bales by -0.7 to 3.5 percentage units (tables 10 to 12), but this could likely be explained by DM loss, which ranged between 1.6% and 15.4% (tables 7 to 9). This is confirmed by the fact that the losses of cellulose mass during storage were not significantly different from 0 (p > 0.05) for all outdoor stored treatments, except for ST bales, which averaged 11.6% loss of cellulose mass (table 10 and 11), and PT bales of RCG in one trial where 4.7% of cellulose was lost (table 11). These were also the treatments with the highest DM losses and thus the greatest opportunity for cellulose loss by spoilage microorganisms. Hemicellulose concentrations changed during storage of dry RCG bales by -3.1 to 2.2 percentage units (tables 10 to 12), whereas hemicellulose concentrations increased 2.0 to 3.1 percentage units in SWG (table 11). Hemicellulose can decrease with time because grasses have enzymes that break down hemicellulose (Dewar et al., 1963). However, the activity of these enzymes has only been measured during ensiling, i.e., under moist, anaerobic conditions (Dewar et al., 1963). On a mass basis, there were only a few cases over the trials where there was a significant loss of hemicellulose during storage: ST for both grasses (average 10.9% loss, tables 10 and 11) and PT and NW in the 2006-2007 trial (table 12). These were treatments with the highest DM losses in their respective trials. Only with PT and NW in the 2006-2007 trial was the hemicellulose loss greater than the cellulose loss on a mass basis.

Ideally, biomass feedstocks should have uniform physical and chemical properties. Moisture content in round bales of perennial grasses stored outdoors was spatially variable (tables 7 to 9), with higher moisture in the base and below the major axis of the bale (fig. 5). Lignin and ash content tended to be higher in the base of bales stored outdoors (table 13). Bales wrapped in sisal twine had the most spatially variable chemical composition (table 13).

WRAPPED AND ENSILED BALE STORAGE

The WE bales had a very pleasant typical ensiled odor when removed and were observed to be uniform in appearance and physical characteristics. Loss of DM averaged 1.1%

Table 10. Aggregate chemical composition and loss of cellulose and hemicellulose in bales of RCG stored on 15 July 2005 and removed on 14 June 2006 after 334 days in storage.[a]

Storage Location and Treatment[b]	Into Storage (% of DM)					Out of Storage (% of DM)					Change During Storage (% units)[c]		Change in Mass During Storage (% of initial dry mass)[d]	
	ADF	NDF	ADL	Ash	CP	ADF	NDF	ADL	Ash	CP	Cellulose	Hemi-Cellulose	Cellulose	Hemi-Cellulose
Outdoor														
ST	39.7 b	70.5 b	5.4 b	7.2	7.3 a	40.8 b	72.5 b	5.4 b	9.2 b	6.2 a	1.0	0.9	-12.6 b	-12.5 b
PT	38.7 b	69.6 ab	5.2 b	7.4	7.5 a	39.6 ab	71.7 b	4.1 a	8.4 ab	6.2 a	2.0	1.2	-1.9 a	-4.0 a
NW	39.4 b	70.2 ab	5.4 b	7.4	9.0 b	40.7 b	73.0 b	4.1 a	8.2 a	6.3 a	2.5	1.5	-0.8 a	-3.2 a
BF	39.2 b	70.2 ab	5.1 ab	7.1	8.4 ab	39.7 ab	71.6 b	3.8 a	7.9 a	6.1 a	1.8	0.8	2.3 a	-0.4 a
Under cover														
IN	39.3 b	70.5 b	5.0 ab	7.0	8.1 a	38.3 a	70.2 ab	3.5 a	7.8 a	7.6 b	0.5	0.6	-1.2 a	-0.6 a
WE	37.4 a	69.0 a	4.9 a	7.6	8.0 a	38.7 a	69.3 a	7.0 c	7.8 a	8.7 b	-0.7	-1.0	3.9 a	-3.4 a
LSD[e] (p = 0.05)	1.1	1.4	0.4	0.6	0.8	1.6	1.8	0.7	0.9	1.2	3.1	2.5	5.9	5.4

[a] RCG = reed canarygrass.
[b] ST = sisal twine, PT = plastic twine, NW = net wrap, BF = breathable film, IN = stored indoors, and WE = wrapped in plastic film tube and ensiled.
[c] Cellulose and hemicellulose estimated from final minus initial concentrations of ADF and ADL (cellulose) and NDF and ADF (hemicellulose).
[d] Change in estimated dry mass of cellulose and hemicellulose during storage as a fraction of initial dry mass.
[e] Averages in the same column followed by different letters are significantly different at 95% confidence.

Table 11. Aggregate chemical composition and loss of cellulose and hemicellulose mass for bales of RCG and SWG stored on 30 August 2005 and removed on 19 June 2006 after 293 days in storage.[a]

Storage Location and Treatment[b]	Into Storage (% of DM)					Removed from Storage (% of DM)					Change During Storage (% units)[c]		Change in Mass During Storage (% of initial dry mass)[d]	
	ADF	NDF	ADL	Ash	CP	ADF	NDF	ADL	Ash	CP	Cellulose	Hemi-Cellulose	Cellulose	Hemi-Cellulose
RCG														
Outdoors														
ST	38.5 a	69.1 ab	5.0	6.4	9.0 c	40.9 c	72.5 b	6.7 c	9.8 b	9.7 c	0.8 ab	1.1 abc	-12.4 a	-11.4 a
PT	37.7 ab	68.7 ab	4.2	6.2	8.7 bc	39.1 ab	72.2 b	4.3 ab	8.0 a	9.0 bc	1.2 ab	2.2 a	-4.7 b	-1.6 b
NW	38.3 a	69.3 ab	4.8	6.9	8.2 abc	40.1 bc	72.5 b	5.1 ab	8.3 ab	8.8 bc	1.5 ab	1.4 ab	-2.7 b	-2.8 b
BF	38.3 a	68.9 ab	4.3	6.2	7.8 ab	38.5 a	71.0 b	4.1 a	7.4 a	8.4 ab	0.4 bc	1.8 a	-3.8 b	0.8 bc
PF	38.5 a	68.8 ab	5.1	7.4	7.5 a	38.8 ab	71.1 b	5.0 ab	8.7 ab	7.8 a	0.4 bc	2.0 a	-0.8 bc	4.4 c
Under cover														
IN	36.8 ab	68.5 a	4.4	6.9	8.1 abc	38.8 ab	71.1 b	4.7 ab	7.1 a	8.9 bc	1.8 a	0.5 bc	2.7 c	-1.3 b
WE	39.6 b	70.2 b	5.8	6.4	8.9 bc	38.6 ab	69.2 a	5.2 ab	7.6 a	11.0 d	-0.4 c	0.0 c	-1.9 b	-0.7 b
LSD[e] (p = 0.05)	1.5	1.5	0.9	1.2	1.0	1.4	1.5	1.0	1.6	0.9	1.1	1.2	4.1	4.6
SWG														
Outdoors														
ST	39.1 bcd	69.8 b	4.2	8.1	5.7 ab	44.4 e	77.5 c	7.2 c	7.9 b	9.2	2.3 ab	2.3	-9.9 a	-8.9 a
PT	40.0 d	72.1 c	4.9	8.0	5.3 ab	43.4 de	77.5 c	5.3 ab	6.0 a	8.4	3.0 ab	2.0	-3.4 b	-4.2 ab
NW	38.8 bc	69.7 b	4.4	8.6	5.0 a	42.8 cd	76.7 c	4.9 ab	6.0 a	8.8	3.5 a	3.1	-1.4 b	-1.9 b
BF	39.3 bcd	69.7 b	4.7	8.9	5.6 ab	42.4 bcd	75.3 bc	5.0 a	5.7 a	9.1	2.8 ab	2.4	-0.2 b	-1.5 b
PF	39.8 c	71.1 bc	4.4	8.3	5.2 ab	41.6 bc	75.4 bc	4.6 a	5.3 a	8.8	1.6 ab	2.4	-2.0 b	-1.7 b
Under cover														
IN	38.7 b	68.7 a	4.6	9.1	6.3 b	40.9 b	74.0 b	4.8 a	6.3 ab	9.7	2.0 ab	3.0	-1.6 b	-0.5 b
WE	36.4 a	66.8 a	4.2	9.4	5.9 ab	38.4 a	69.3 a	5.8 b	5.8 a	9.8	0.5 b	0.5	-0.5 b	-0.4 b
LSD[e] (p = 0.05)	1.0	1.9	0.7	1.4	1.1	1.5	2.5	0.9	1.8	1.6	2.2	3.2	3.5	4.7

[a] RCG = reed canarygrass; SWG = switchgrass.
[b] ST = sisal twine, PT = plastic twine, NW = net wrap, BF = breathable film, PF = plastic film, IN = stored indoors, and WE = wrapped in plastic film tube and ensiled.
[c] Cellulose and hemicellulose estimated from final minus initial concentrations of ADF and ADL (cellulose) and NDF and ADF (hemicellulose).
[d] Change in estimated dry mass of cellulose and hemicellulose during storage as a fraction of initial dry mass.
[e] Averages in the same column followed by different letters are significantly different at 95% confidence.

Table 12. Aggregate chemical composition and loss of cellulose and hemicellulose mass for bales of RCG stored on 18 July 2006 and removed on 25 May 2007 after 311 days in storage.[a]

Storage Location and Treatment[b]	Into Storage (% of DM)					Out of Storage (% of DM)					Change During Storage (% units)[c]		Change in Mass During Storage (% of initial dry mass)[d]	
	ADF	NDF	ADL	Ash	CP	ADF	NDF	ADL	Ash	CP	Cellulose	Hemi-Cellulose	Cellulose	Hemi-Cellulose
Outdoors														
PT	40.5	71.3	6.3 a	8.5 a	8.2	45.1 b	72.9 a	8.9 b	9.7 b	7.3	2.2	-3.1 b	-4.0	-18.8 a
NW	39.3	70.2	6.3 a	9.2 ab	7.5	44.5 ab	74.5 ab	9.2 b	9.4 ab	7.2	2.3	-0.8 a	-0.3	-9.3 b
BF	39.8	71.1	6.5 a	8.3 a	7.2	44.3 ab	75.8 b	8.7 ab	8.6 ab	6.6	2.3	0.1 a	-0.9	-2.6 c
PF	40.2	70.8	6.2 a	8.8 ab	8.3	43.5 ab	74.0 ab	9.2 b	9.2 ab	7.1	0.3	-0.1 a	-3.7	-4.9 bc
Under cover														
BT	40.6	71.1	6.5 a	8.9 ab	7.4	42.5 a	72.3 a	7.5 a	8.3 a	7.1	0.9	-0.7 a	0.1	-5.2 bc
IN	41.0	70.3	7.2 b	10.4 b	7.9	42.6 a	72.3 a	7.5 a	8.9 ab	6.4	1.2	0.4 a	0.8	-1.2 c
LSD[e] (p = 0.05)	1.7	1.5	0.5	1.6	2.2	2.3	2.5	1.2	1.1	0.9	2.0	2.1	6.3	6.3

[a] RCG = reed canarygrass.
[b] PT = plastic twine, NW = net wrap, BF = breathable film, PF = plastic film, IN = stored indoors, and BT = stored under a bale tarp.
[c] Cellulose and hemicellulose estimated from final minus initial concentrations of ADF and ADL (cellulose) and NDF and ADF (hemicellulose).
[d] Change in estimated dry mass of cellulose and hemicellulose during storage as a fraction of initial dry mass.
[e] Averages in the same column followed by different letters are significantly different at 95% confidence.
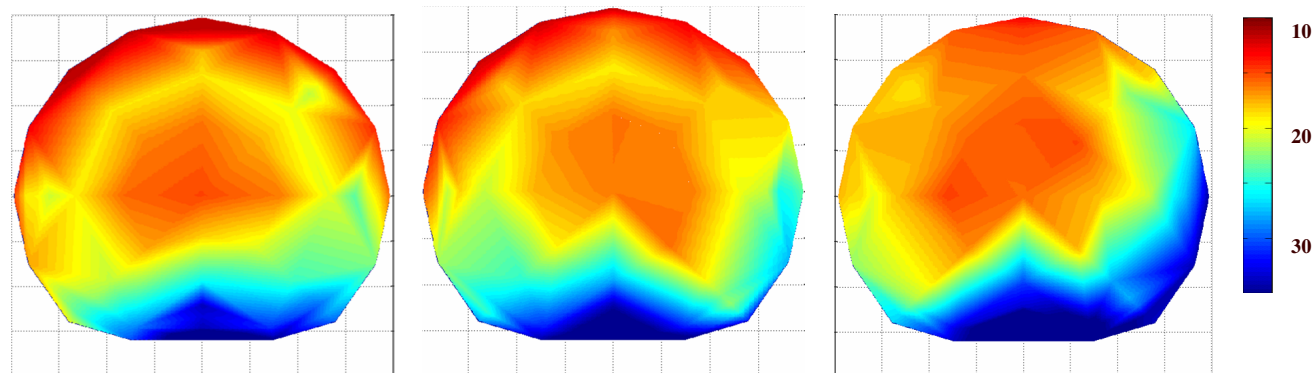

Figure 5. Example of relative spatial moisture distribution of SWG bales of (left to right, scale on far right) of breathable film (BF), net wrap (NW), and plastic twine wrap (PT) bales stored outdoors on the ground for 293 days. Moisture (percent wet basis) was estimated at 50 locations using a conductance moisture sensor at the time the bales were removed from storage.

over the two storage studies that included WE bales (table 14). Respiration losses would have resulted in a rise in moisture during storage because stiochiometrically 60% of the mass of the respired carbohydrates would have remained in the bale as H_2O (Pitt, 1990). The average absolute difference between the final and initial bale moisture was 0.6 percentage units, which corresponds to a theoretical DM loss of 1.4%. Losses with wrapped bale silage have been reported to be in the range of 3% to 12% (Huhnke et al., 1997; Shinners et al., 2009a). After 11 months in storage, the low DM loss in WE bales shows the viability of long-term preservation of biomass grasses by ensiling. Cell wall polysaccharides converted to acids by fermentation during storage could be con-sidered a loss if downstream biochemical processes cannot convert these acids to useful products. Fermentation acids were less than 3% of DM in this study (table 14). Moisture content has an important influence on the costs associated with shipping biomass. Preservation of biomass DM by ensiling at moistures below 50% was successful. Ensiling at moisture contents below those typically considered acceptable for conserving animal feed means that considerably less water would need to be shipped in the biomass feedstock. For instance, 44% more DM can be shipped per truckload when biomass moisture is 35% (w.b.) compared to when it is 55% (w.b.), provided the density allows legal shipping weight limits to be achieved.

Table 13. Chemical composition of RCG and SWG when removed from storage on 19 June 2006 after 293 days in storage by sampling location in the bale.[a]

Wrap Type[b]	Sampling Location on Bale	RCG Chemical Composition (% of DM)				SWG Chemical Composition (% of DM)			
		ADF	NDF	ADL	Ash	ADF	NDF	ADL	Ash
ST	Outer layer	41.0 a	74.1 b	5.2 a	7.7 a	45.1 b	79.0 b	5.7 a	6.5 a
	Core	39.7 a	72.0 ab	4.3 a	7.3 a	43.5 a	77.8 b	5.6 a	5.6 a
	Base	46.4 b	70.9 a	22.0 b	27.0 b	46.8 b	70.0 a	20.9 b	24.7 b
	LSD[c] (p = 0.05)	3.3	2.0	4.9	5.7	1.3	2.4	4.1	3.1
PT	Outer layer	39.4	72.3	4.4 a	8.6 ab	44.8 b	79.2 b	5.5 ab	5.9 a
	Core	38.9	72.2	4.1 a	7.3 a	42.4 a	76.4 a	5.1 a	5.8 a
	Base	39.3	71.9	5.4 b	9.6 b	43.7 ab	76.8 a	6.2 b	7.4 b
	LSD[c] (p = 0.05)	0.9	1.1	0.9	1.4	1.3	2.0	0.8	0.9
NW	Outer layer	40.3	72.8	5.0 a	7.9 a	42.9	76.7	4.9	6.2 ab
	Core	39.9	72.5	5.0 a	8.4 a	42.7	76.8	4.9	5.8 a
	Base	40.3	71.4	6.6 b	10.2 b	43.3	75.9	5.4	6.7 b
	LSD[c] (p = 0.05)	1.4	1.4	0.6	1.0	1.3	1.6	1.2	0.7
IN	Outer layer	39.2	70.8	4.8	7.2	40.4	74.3	4.1	7.1
	Core	38.7	71.3	4.6	7.4	41.2	73.8	4.6	7.0
	Base	38.3	70.8	4.5	7.3	41.6	74.2	4.6	7.2
	LSD[c] (p = 0.05)	0.9	1.1	0.5	0.9	1.2	1.4	0.7	0.6

[a] RCG = reed canarygrass; SWG = switchgrass.
[b] ST = sisal twine, PT = plastic twine, NW = net wrap, and IN = stored indoors.
[c] Averages in the same column followed by different letters are significantly different at 95% confidence.

Table 14. pH and fermentation products for RCG and SWG bales wrapped in tube of plastic film and preserved by ensiling.[a]

	Moisture(% w.b.)		Days Stored	DM Loss (% of total)	pH	Fermentation Products (% of DM)			
	Stored	Removed				Lactic Acid	Acetic Acid	Ethanol	Total Acids
RCG[b]	33.9	34.4	334	0.3	5.9	0.25	0.19	0.41	0.91
RCG[c]	36.8	37.5	293	0.8	5.4	0.65	0.54	0.72	2.13
SWG[c]	49.0	49.5	293	2.0	4.9	0.93	0.68	0.71	2.55

[a] RCG = reed canarygrass; SWG = switchgrass.
[b] Ensiled in July 2005 and removed in June 2006 (see tables 7 and 10).
[c] Ensiled in August 2005 and removed in June 2006 (see tables 8 and 11).

SUMMARY

In a single-cut system, RCG yield was 21% less than SWG yield. RCG yield was 27% greater using a two-cutting system. When the crops were left standing over winter and harvested in the spring, DM yields were reduced by 17% and 26% for SWG and RCG, respectively.

Although SWG produced greater yields than RCG, even in the northern location tested, SWG required considerable weed control due its slow spring growth, so production costs of SWG may be greater than those of RCG.

When the crops were placed in a wide swath by tedding, it was possible to achieve baling moisture (<20% w.b.) in a single day. The drying rate constants for both crops were greater than those typically reported for forage crops like alfalfa or forage grasses. When crop yield was similar, SWG tended to dry faster than RCG.

Round bale density averaged 163 kg DM m^{-3} with no significant differences between crops or type of wrap (twine or net). The bale density was only slightly less than those reported for alfalfa or forage grasses.

Baling productivity was 47% greater with SWG compared to RCG because the former crop more easily fed into the baler throat due to its more compact windrow structure. Baling with net wrap improved baling productivity by 46% compared to baling with twine.

Dry round bales stored outdoors for 293 to 334 days averaged 3.8%, 4.8%, 7.5%, 8.7%, and 14.9% DM loss for bales wrapped with plastic film, breathable film, net wrap, plastic twine, and sisal twine, respectively. Bales stored under cover averaged 3.0% DM loss.

No matter the type of wrap, bales stored outdoors in direct contact with the ground had higher moisture in the outer layer and base than in the core. The average moisture content of the outer layer, core, and base of bales wrapped with twine or net was 20.8%, 15.6%, and 48.4%, respectively.

The chemical composition of the bale varied spatially when removed from storage, and there was considerable loss of cellulose and hemicellulose mass during storage. The most uniform dry biomass feedstock was generated by storing dry bales under cover.

Low-moisture anaerobic storage of round bales of the grasses was very successful. Preservation by ensiling in a film tube produced average DM losses of 1.1% when stored at average moisture of 39.9% (w.b.) with less than 3% of DM as fermentation acids.

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