Switchgrass Biomass Quality as Affected by Nitrogen Rate, Harvest Time, and Storage

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ABSTRACT

The purpose of this study was to assess the changes in switchgrass (*Panicum virgatum* L.) biomass quality as affected by N rate, harvest time, and storage. This research was conducted near Bristol, SD, in 2010 and 2011. Treatments included three N rates (0, 56, and 112 kg N ha^{-1}) applied annually and each N rate replicated four times. After a killing frost, all of the plots were harvested and baled in large round bales in October 2010 and November 2011. An area of about 30 m^2 from each plot was left unharvested to represent storage of standing switchgrass over the winter and to determine dry matter yields. Switchgrass was analyzed for hemicellulose, cellulose, lignin, mineral elements, N, and C. In the first season, storage of the fall harvested switchgrass bales numerically increased the concentrations of hemicellulose, lignin, and N. In the second season, they increased significantly. Mineral elements significantly increased in both sampling seasons. Delaying harvest until spring decreased lignin, N, and mineral elements concentration, and increased cellulose and hemicellulose concentrations, but also reduced biomass yield. Results from this study suggest that delaying the switchgrass harvest until spring increased the overall feedstock quality for ethanol production, but yield reductions must be considered to determine the overall economic impact of a delayed harvest.

Core Ideas

- Switchgrass, being an efficient perennial biofuel crop, can be used as an alternative to fossil fuels and help in the sustainability of energy. Thus, it is important that we understand the effect of storing switchgrass for extended periods of time.
- Storing switchgrass for an extended period may have an impact on quality and yield.
- Storing switchgrass in bales or as a standing crop in the field are two storage methods assessed in this study.

Published in Agron. J. 109:86–96 (2017)
doi:10.2134/agronj2016.07.0380
Received 2 July 2016
Accepted 30 Sept. 2016
Available freely online through the author-supported open access option

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SWITCHGRASS is a warm-season perennial C_4 grass that is native to North America. It is leafy and vigorous, belongs to the caespitose grasses, and grows to a height of 1.0 to 3.0 m (Quatrocchi, 2006). Switchgrass has been evaluated as a renewable bioenergy feedstock because it has high yield potential on low quality lands (marginal soils that are not suited for crops) with relatively low nutrient demand (Lewandowski et al., 2003). However, applying N fertilizer (ranging from 50–200 kg N ha^{-1}) has been shown to increase switchgrass biomass yield in some U.S. locations (Lemus et al., 2008; Kering et al., 2012; Hong et al., 2014; Sadeghpour et al., 2014). A study conducted by Mbonimpa et al. (2015) discussed the benefits of switchgrass to both soils and the environment. A few examples include improved soil quality (Lee et al., 2007), increased C sequestration (Schmer et al., 2011), and reduced greenhouse gas emissions (Davis et al., 2012). More than two decades ago, the U.S. Department of Energy (U.S.-DOE) selected switchgrass as a model herbaceous bioenergy crop (McLaughlin and Walsh, 1998; Lemus et al., 2008). Further, switchgrass has been evaluated as a bioenergy crop across much of the central and eastern United States (Casler and Boe, 2003; Berdahl et al., 2005; Cassida et al., 2005). There is increased interest in using switchgrass as a bioenergy crop compared with other crops because of its low ash and high energy content (Mani et al., 2004).

Other factors, in addition to N, that can affect switchgrass yield and quality include harvest time and storage length and conditions. Biomass feedstock storage, either in bales or by delaying the harvest time, is usually needed for 6 to 12 mo to ensure continuous availability of feedstock for generating energy during the winter and until reaching the next harvest season. During storage, changes in the structural and extractable constituents take place, which may change the quality of the biomass feedstock as a source for biofuel (Wiselogel et al., 1996). In general, favorable bioenergy crops should have high concentrations of cell wall constituents (e.g., hemicellulose and cellulose), low concentration of N, mineral elements, ash, and moisture content (Lewandowski and Kicherer, 1997; McKendry, 2002a). However, higher lignin concentrations are not desirable in the fermentation process to produce ethanol because lignin may reduce cellulose and polysaccharide availability (Sun and Cheng, 2002).

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Previous studies revealed that delaying switchgrass harvest until after a killing frost can allow mineral elements to translocate from the shoots to the roots, which subsequently reduce their concentrations in the aboveground biomass; however, delaying harvest until the following spring often results in a reduction in biomass yield (Adler et al., 2006; Lee et al., 2009; McLaughlin et al., 1996; Mulkey et al., 2006; Parrish and Fike, 2005; Sanderson and Wolf, 1995). In parts of the northern United States, over-wintering biomass may create harvest issues as it will be more susceptible to lodging from snowfall (Tahir et al., 2011).

Quality of a bioenergy crop depends on the conversion method. For example, reduced concentrations of mineral elements are desirable for thermochemical and direct combustion methods because high concentrations of these elements can become air pollutants such as N and sulfur oxides, and can form fusible ash causing slagging, corrosion, and fouling of boilers, which in turn reduce the efficacy of the combustion process (Adler et al., 2006; Jørgensen, 1997; Lewandowski and Kicherer, 1997; Miles et al., 1996; Tillman, 2000). Concentrations of the inorganic elements such as Ca, K, P, Mg, and Na are the main components of the ash content in herbaceous biomass (Agblevor and Besler, 1996). Thus, if they increase, the ash content will increase, which passively affects the quality of the biomass feedstock as a bioenergy source. Similarly, an increase of these elements during pyrolysis may cause problems for combustion boilers and diesel engines (Agblevor and Besler, 1996). Although delaying harvest from fall to spring decreased switchgrass yield by ~40% in Pennsylvania, mineral element concentrations decreased as well, which is a desirable quality indicator for direct combustion (Adler et al., 2006; Lewandowski and Heinz, 2003).

For the continuity of using switchgrass biomass as a source of biofuel, storage of the biomass is inevitable from the current to the next harvesting season. During this storage period, changes may occur in the extractable and structural composition of the switchgrass biomass (Wiselogel et al., 1996), which may decrease or increase the quality of the biomass depending on the targeted conversion technique. The ability to store switchgrass for extended periods (e.g., 6–12 mo) while minimizing yield and quality losses is critical. The objectives of this study were to (i) determine effects of N fertilization on the changes in biomass quality such as structural components (fiber constituents) and chemical composition during a storage period of 7 mo after harvesting in two growing seasons (2010 and 2011) and (ii) to assess the biomass quality when delaying the harvest time from fall to spring under different rates of N in the two growing seasons.

MATERIALS AND METHODS

Site Description and Experimental Design

The experiment site was located near Bristol, SD (45°16′25″ N, 97°50′13″ W). Soils of the experimental site were developed from calcareous glacial till parent material and consist of the following soil series Aastad (fine-loamy, mixed, frigid Pachic Udic Haploboroll), Barnes (fine-loamy, mixed, frigid Udic Haploboroll), Buse (fine-loamy, mixed, superactive, frigid Typic Calciudoll), Nutley (fine, smectitic, frigid Chromic Hapludert), Forman (fine-loamy, mixed, superactive, frigid Calcic Argiudoll), and Sinai (fine, smectitic, frigid Typic Hapludert) (NRCS Staff, 2015a). The daily average temperature ranges from –19°C in January to 29°C in July, and the mean annual precipitation is 533 mm (NRCS Staff, 2015b).

The experimental design was a randomized complete block with three N treatments (0, 56, and 112 kg N ha^{-1}) and four replicates. Each plot had a width of 21.3 m and a length of approximately 366 m, and one to two large round bales were harvested from the length of the center of each plot. Switchgrass cultivar Sunburst was planted into soybean (*Glycine max* L.) stubble with a Truax no-till drill (Truax Company Inc., New Hope, MN) on 17 May 2008 at a rate of 11.2 kg pure live seed ha^{-1}. During the two growing seasons of this study, N was applied as urea $[CO(NH_2)_2]$ once annually on 2 June 2010 and 14 June 2011. The site was not harvested in 2009. Herbicide was applied on 19 July 2008 with 3,7-dichloro-8-quinolinecarboxylic acid and 1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine. Similarly, on 24 June 2010 and 18 May 2011, 1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine and N-[phosphonomethyl]-glycine were applied, respectively, to control broadleaf and grassy weeds.

Field Sampling

In the current work, two growing seasons were used: the first season was in 2010 and the second was in 2011. Switchgrass was cut at a stubble height of approximately 10 cm and baled using a large round baler on 5 Oct. 2010 (for the first season), and 3 Nov. 2011 (for the second season), and the approximate bale dimension was 1.5 by 1.8 m. Thereafter, bale core samples were collected monthly until May. The moisture concentration of bale core samples at harvest averaged 190 and 97 g kg^{-1} in 2010 and 2011, respectively, indicating that biomass was sufficiently dry for baling. During the harvesting process, a small area (3 by 10 m) in each plot was left unharvested (i.e., plants were left standing in the field) to collect standing switchgrass samples (0.53 m^2) from the field at the same time core samples were taken from bales, and this area was used to monitor the quality and yield changes in standing switchgrass during the winter and spring. Core samples from bales (approximately 500 g total) were collected monthly from November 2010 to May 2011 (the first season), and from December 2011 to May 2012 (the second season) from the center of each large bale using a hay probe (1.9 cm in width and 76.2 cm in length) attached to an electric drill. Bales were stored unprotected at a well-drained upland area of the field (each bale was 5 m away from other bales) throughout the sampling period. Samples from the standing plants were manually collected using rice knives in the first season in December 2010, April 2011, and May 2011. However, for the second season, samples were collected monthly from December 2011 to May 2012. All samples were oven dried at 60°C for 48 h in a forced-air oven. Dried samples were ground in a Wiley mill (Thomas–Wiley Co., Philadelphia, PA) to pass a 2-mm screen, and were reground to uniformity using a UDY-Cyclone impact mill (UDY Corporation, Fort Collins, CO) to pass a 1-mm screen. Ground samples were stored in plastic containers pending analyses.

Biomass Quality Analyses

Carbon and N content in all of the samples were determined following the dry combustion method (Nelson et al., 1996) using the LECO C&N 2000 analyzer (LECO Corp., St Joseph, MI). Neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) were determined sequentially using the ANKOM 200 fiber analyzer (ANKOM Technology Corp., Fairport, NY) following the ANKOM procedures (Mulkey et al., 2006). Hemicellulose was calculated by subtracting ADF from

NDF, cellulose was calculated by subtracting ADL from ADF (Lemus et al., 2008). To measure mineral elements, portions of the ground samples were digested by nitric acid in a microwave following which the concentrations of B, Ca, Fe, K, Mg, Mn, Na, P, and S were determined using the Inductively Couple Plasma (ICP) spectroscopy technique (SPECTRO Analytical Instruments Inc., Boschstr, Germany) (Undersander et al., 1993).

Statistical Analyses

Statistical comparisons of differences in all of the measured data such as fiber constituents, nutrients, and minerals concentrations among the three N rates and the time of harvest for 2010 and 2011 were obtained using the pairwise differences method to compare LS means by a mixed model using the GLIMMIX procedure in SAS 9.3 software (SAS Institute,

Table 1. Concentration of hemicellulose, cellulose, and lignin in switchgrass bales and in standing switchgrass as impacted by different sampling dates and N rates during 2010–2011 and 2011–2012.

		Hemicellulose				Cellulose				Lignin		
Sampling date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
			g kg^{-1}				g kg^{-1}				g kg^{-1}	
Baled switchgrass (2010–2011)												
5 Nov. 2010	249b	250ab‡	248ab	249b	372ab	366ab	379ab	373ab	121a	116c	127a	119b
7 Dec. 2010	248b	248b	255ab	240b	378a	369ab	388ab	374ab	127a	129a	125a	131ab
11 Jan. 2011	251b	253ab	244b	257ab	371ab	366ab	385ab	361b	125a	126ab	121a	129ab
24 Feb. 2011	260ab	265a	259ab	259ab	373ab	374a	378ab	367b	125a	119bc	127a	129ab
17 Mar. 2011	254b	260ab	259ab	244b	367b	364b	373b	365b	128a	124abc	123a	138a
21 Apr. 2011	263ab	258ab	266ab	264ab	377a	370ab	379ab	382a	123a	123abc	127a	119b
11 May 2011	271a	257ab	269a	287a	377a	370ab	393a	368b	128a	130a	122a	132ab
Analysis of variance *P* > *F*												
N rate		0.95				<0.0001				0.30		
Time		0.03				0.06				0.42		
N rate × Time		0.64				0.12				0.36		
Baled switchgrass (2011–2012)												
3 Nov. 2011	199c	207c	197c	194c	351d	343d	355d	354d	103c	99c	108cd	104b
8 Dec. 2011	237b	241b	237b	232b	356d	344d	367cd	358d	99c	95c	103d	100b
6 Jan. 2012	241b	244b	241b	238b	382c	371c	388bc	387c	111b	108b	111bc	115a
13 Feb. 2012	242b	246b	242b	237b	384c	374bc	393b	384c	116a	111ab	119ab	118a
19 Mar. 2012	243b	250b	243b	235b	384c	377bc	384bc	392c	116a	115a	115abc	118a
10 Apr. 2012	286a	294a	273a	289a	396b	386b	395b	406b	115ab	111ab	118ab	117a
18 May 2012	290a	291a	289a	291a	418a	410a	423a	422a	119a	116a	122a	120a
Analysis of variance *P* > *F*												
N rate		0.06				<0.0001				<0.0001		
Time		<0.0001				<0.0001				<0.0001		
N rate × Time		0.93				0.85				0.81		
Standing switchgrass (2010–2011)												
7 Dec. 2010	266a	266a	264a	268a	381b	380a	389b	374b	135a	130a	137a	137a
21 Apr. 2011	249b	254ab	245b	248b	400a	384b	407a	409a	137a	132a	137a	143a
11 May 2011	251b	247b	244b	261ab	408a	400a	407a	417a	127a	129a	136a	116a
Analysis of variance *P* > *F*												
N rate		0.14				0.06				0.55		
Time		0.0002				0.0003				0.26		
N rate × Time		0.26				0.18				0.44		
Standing switchgrass (2011–2012)												
8 Dec. 2011	240ab	244a	236b	240a	389c	385c	390d	391c	126a	124a	130a	125b
6 Jan. 2012	247a	243a	253a	245a	401b	402bc	396cd	404bc	126a	125a	125a	130b
13 Feb. 2012	243a	245a	238b	245a	410ab	409b	407bc	413ab	128a	127a	126a	130b
19 Mar. 2012	233b	233ab	233bc	233ab	413a	403bc	416ab	419ab	128a	126a	126a	132ab
10 Apr. 2012	222c	233ab	220cd	213b	420a	408b	426a	427a	131a	119a	127a	145ab
18 May 2012	221c	225b	215d	225ab	418a	428a	420ab	407ab	135a	121a	132a	153a
Analysis of variance *P* > *F*												
N rate		0.39				0.47				0.001		
Time		<0.0001				<0.0001				0.35		
N rate × Time		0.58				0.15				0.11		

† Nitrogen treatments rates were 0, 56, and 112 kg N ha^{-1}.

‡ Same letters in the same column during the same season for the same N treatment means no significant differences. There were no significant differences between each fiber constituent under the three N rates in each separate month.

2011). Analysis of variance was used to test the fixed effects on the fiber constituents and mineral elements based on the mixed model. Similarly, the time effects on these parameters were tested using another mixed model. The analyses were done with sampling dates and N rates as fixed effects and block as a random effect. Significance was determined at a = 0.05 level for all statistical analyses in this study.

RESULTS AND DISCUSSION

Baled Switchgrass Biomass Quality

During the storage time of the first season (2010–2011) and under the N treatment of 0 kg N ha^{-1}, the concentrations of hemicellulose did not significantly change in spite of its increase from 250 to 257 g kg^{-1} in November 2010 and May 2011, respectively (Table 1). The same trend for hemicellulose concentration was found under the 56 kg N ha^{-1} treatment. However, hemicellulose concentration under the 112 kg N ha^{-1} treatment significantly increased from 249 to 287 g kg^{-1} in November 2010 and May 2011, respectively (Table 1). Average of hemicellulose in all N rates significantly increased from November 2010 to May 2011 (Table 1). This increase in hemicellulose concentration could be due to the increased weathering of biomass and microbial activity that reduce the total C concentration as a consequence of decomposing non-structural carbohydrates (Wiselogel et al., 1996).

Generally, cellulose and lignin concentrations under all of the three N treatments did not significantly change from November 2010 to May 2011 (Table 1). Under 0 kg N ha^{-1}, lignin concentration significantly increased (from 116 to 130 g kg^{-1}) between November 2010 and May 2011. This change may be a result of sampling variability or through the loss of non-structural plant components. Our results agreed with those reported by Adler et al. (2006) in Pennsylvania and Lemus et al. (2008) in Iowa. The increase in hemicellulose and cellulose is desirable in generating energy; however, the increase in lignin concentration is not favorable because lignin reduces the availability of hemicellulose and cellulose in fermentation and producing ethanol (McKendry, 2002a; Sun and Cheng, 2002). For individual months, N rate had no effect on hemicellulose, cellulose, or lignin concentrations (Table 1).

In the second season (2011– 2012), the concentrations of hemicellulose, cellulose, and lignin under all of the N rates significantly increased from November 2011 to May 2012. For example, at the rate of 56 kg N ha^{-1}, hemicellulose increased by ~ 47% (from 197 to 289 g kg^{-1}), cellulose by 18% (from 355 to 423 g kg^{-1}), and lignin by 13% (from 108 to 122 g kg^{-1}) (Table 1). Interestingly, the concentrations of the fiber constituents did not significantly change during the coldest storage period (December until February), and they increased when the temperature increased in April and May. This trend could be related to the weather (higher temperature) impact on activity of the decomposing microorganisms. Hemicellulose, cellulose, and lignin concentrations were not significantly different among the three N rates within a sampling date.

In the first season, most of the mineral elements in the baled switchgrass increased monthly (Table 2). For example, under the N rate of 56 kg N ha^{-1}, Ca concentration increased from November 2010 to May 2011 by 11% (from 8.0 to 8.9 g kg^{-1}), K increased by 8% (from 5.2 to 5.6 g kg^{-1}), Mg increased by 13% (from 3.1 to 3.5 g kg^{-1}), and P increased by 9% (from 6.8 to 7.4 g kg^{-1}) (Table 2). During biomass storage in the bales in the first season, the mineral elements concentration in the samples could be ranked as Ca > *P* > Na > K > Mg. The higher concentration of Ca was attributed to the abundance of Ca in the soil. However, concentrations of B, Fe, Mn, and S changed only slightly with no clear trend from November 2010 to May 2011 (Table 2).

The average precipitation in 2011 was 6.5% lower than the long-term annual average precipitation, but in 2010 it was 17.5% higher than the long-term annual average precipitation (Mbonimpa et al., 2015). Because the second season encountered drier conditions, concentrations of all of the mineral elements, except K, were less than were those of the first season (Tables 2 and 3). During drier conditions, plants tend to take up more K compared to other elements because K plays a significant role in increasing the osmotic potential of the plant vacuoles, which in turn improves tolerance to drought (Marschner, 2006). The concentration of mineral elements of the baled samples in the second season changed slightly but with no significant differences, with the exception of K (Table 3). In the 56 kg N ha^{-1} treatment, K concentration decreased from 7.4 to 6.9 g kg^{-1} from November 2011 to May 2012, respectively (Table 3). Unlike the first season, mineral element concentrations were ranked as K > Ca > Mg > *P* > Na. Like the first season (2010– 2011), N did not impact mineral element concentrations in each separate month, which agreed with Lemus et al. (2008).

Nitrogen concentration in the baled switchgrass biomass during the first season (2010–2011) tended to increase with no significant difference from November 2010 to May 2011 within each individual N rate (Fig. 1). For example, N concentration increased by 15% (from 4.0 to 4.6 g kg^{-1}) under the rate of 0 kg N ha^{-1}, by 14% (from 4.3 to 4.9 g kg^{-1}) under the rate of 56 kg N ha^{-1}, and by 13% (from 5.5 to 6.2 g kg^{-1}) under the rate of 112 kg N ha^{-1} (Fig. 1). Furthermore, by increasing the rate of applied N, plants could take up more N (Reynolds et al., 2000), which was evident as there was a significant increase in N concentration in the biomass with an increase in

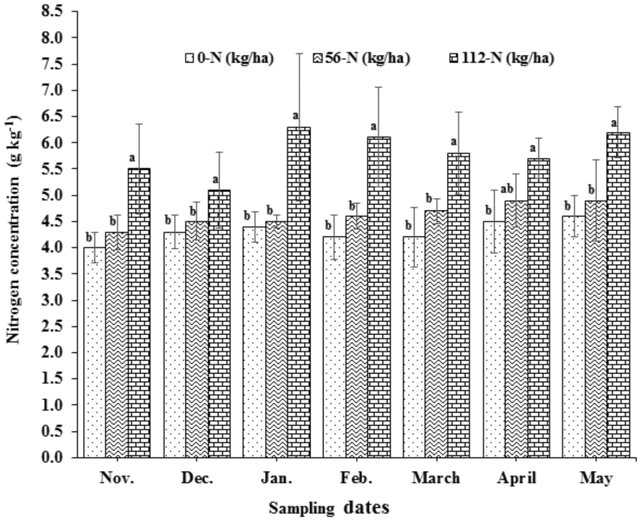

Fig. 1. Nitrogen concentration in switchgrass biomass bales as affected by sampling dates and N rates in the 2010–2011 season. Error bars represent standard deviation, and the same letters shown on the bars of the three N rates at the same sampling date means no significant difference.

the applied N within each separate month and within the two seasons (Fig. 1 and 2). For example, in December of 2011 (the second season), N concentration was the lowest (3.4 g kg^{-1}) under the rate of 0 kg N ha^{-1}, intermediate (3.8 g kg^{-1}) under the rate of 56 kg N ha^{-1}, and the highest (4.6 g kg^{-1}) under the rate of 112 kg N ha^{-1} (Fig. 2). During the second season (2011–2012), however, N concentration changed only slightly each month from November 2011 to May 2012, with no clear trend. These changes in the switchgrass N concentration, must be balanced with increasing N_2O emissions with increasing N application rates.

In the baled switchgrass biomass, C concentration significantly changed among sampling dates within each N rate in the first season (2010–2011) (Fig. 3). The major change took place within the first few months after harvest (Fig. 3). The C concentration significantly declined from November to December for all of the N rates. This drastic decline could be due to the microbial activity that decomposed the non-structural C (e.g., carbohydrates) (Wiselogel et al., 1996). Then, within January and February (lowest air temperature through the storage period), there was no significant differences in the changes in C concentration. When the temperatures increased in March, the

Table 2. Concentration of mineral elements under different N rates and sampling dates in switchgrass bales during 2010–2011.

		B				Ca				Fe		
Sampling date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
		mg kg^{-1}				mg kg^{-1}				mg kg^{-1}		
5 Nov. 2010	0.44a	0.43a†	0.44a	0.46a	8.56b	8.8c	8.0c	8.9c	0.28a	0.35a	0.22b	0.26b
7 Dec. 2010	0.29e	0.29c	0.28c	0.28d	9.71a	9.5bc	8.9b	11.3a	0.28a	0.27a	0.24ab	0.40a
11 Jan. 2011	0.33d	0.31c	0.32c	0.35c	10.24a	10.5a	9.2b	11.1ab	0.29a	0.27a	0.23ab	0.36ab
24 Feb. 2011	0.36c	0.37b	0.37b	0.35c	9.92a	9.7ab	9.4ab	10.7ab	0.25a	0.26a	0.25ab	0.25b
17 Mar. 2011	0.4b	0.40ab	0.38b	0.42ab	10.41a	9.8ab	10.1a	11.3a	0.31a	0.35a	0.28a	0.29ab
21 Apr. 2011	0.41b	0.42a	0.41ab	0.40b	9.83a	10.1ab	9.3ab	10.1b	0.25a	0.25a	0.23ab	0.25b
11 May 2011	0.41b	0.41ab	0.44a	0.39bc	10.03a	10.3ab	8.9b	11.4a	0.27a	0.25a	0.26ab	0.32ab
Analysis of variance *P* > *F*												
N rate	0.99				<0.0001				0.05			
Time	<0.0001				<0.0001				0.53			
N rate × Time	0.1624				0.28				0.52			
		K				Mg				Mn		
Sampling date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
		mg kg^{-1}				mg kg^{-1}				mg kg^{-1}		
5 Nov. 2010	5.2a	4.4ab	5.2a	6.1a	3.2b	2.9c	3.1c	3.5c	0.09a	0.10ab	0.07c	0.10a
7 Dec. 2010	4.5a	3.7c	4.0b	4.5a	3.6a	3.2b	3.7a	3.9ab	0.10a	0.09b	0.09b	0.09a
11 Jan. 2011	4.7a	4.2abc	4.2b	5.7a	3.7a	3.4a	3.6a	4.1ab	0.11a	0.10ab	0.08bc	0.13a
24 Feb. 2011	4.8a	3.9bc	4.5b	5.9a	3.5ab	3.2b	3.3bc	3.9ab	0.10a	0.09b	0.09b	0.12a
17 Mar. 2011	4.7a	4.0bc	4.5b	5.5a	3.6a	3.2b	3.6a	4.0ab	0.11a	0.10ab	0.11a	0.13a
21 Apr. 2011	4.5a	4.2abc	4.5b	5.0a	3.4ab	3.2b	3.3bc	3.8b	0.10a	0.11ab	0.09b	0.09a
11 May 2011	5.1a	4.5a	5.6a	5.4a	3.6a	3.3ab	3.5ab	4.2a	0.11a	0.13a	0.08bc	0.12a
Analysis of variance *P* > *F*												
N rate	<0.0001				<0.0001				0.007			
Time	0.75				<0.0001				0.76			
N rate × Time	0.93				0.63				0.66			
		Na				P				S		
Sampling date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
		mg kg^{-1}				mg kg^{-1}				mg kg^{-1}		
5 Nov. 2010	7.0ab	7.4a	7.1ab	6.6a	7.4ab	7.7a	6.8ab	7.8ab	1.4a	1.4abc	1.3ab	1.6a
7 Dec. 2010	6.7bc	6.6ab	6.5ab	7.2a	4.7d	4.5d	4.4c	5.1c	1.2a	1.1d	1.0d	1.3a
11 Jan. 2011	7.4a	7.2ab	7.7a	7.5a	6.2c	6.3c	5.4c	6.9b	1.4a	1.3bc	1.1cd	1.7a
24 Feb. 2011	6.8bc	6.9ab	6.6ab	6.8a	6.6c	6.6c	6.0bc	7.1b	1.3a	1.2c	1.2bcd	1.6a
17 Mar. 2011	6.6bc	6.2b	7.0ab	6.6a	6.8bc	6.7bc	6.4b	7.4ab	1.4a	1.3bc	1.4a	1.6a
21 Apr. 2011	6.3c	6.3ab	5.9b	6.7a	6.9bc	7.4ab	6.1bc	7.2b	1.3a	1.4ab	1.3ab	1.3a
11 May 2011	6.5bc	6.5ab	6.2b	7.0a	7.8a	7.9a	7.4a	8.4a	1.4a	1.5a	1.3ab	1.7a
Analysis of variance *P* > *F*												
N rate	0.51				0.0002				<0.0001			
Time	0.03				<0.0001				0.76			
N rate × Time	0.64				0.99				0.87			

† Same letters in the same column for the same N treatment means no significant differences; different letters in the same column for the same N treatment means significant differences. There were no significant differences in the concentrations of elements among the three rates of N.

C concentrations declined again. In spite of the warmer temperatures in April and May, the C concentrations increased. In the second season (2011–2012), the C concentration significantly changed by sampling dates from November 2011 to May 2012 within each individual N rate treatment (Fig. 4). The lowest values were observed in the warm months and the highest values were observed in the coldest months. These changes in C concentration could be attributed to the change of temperature that affected the microbial activity. Furthermore, C concentration slightly changed among N rates within each sampling date (Fig. 4).

Because the second growing season (2011– 2012) encountered drier conditions compared with the first growing season (2010– 2011) (Mbonimpa et al., 2015), the concentrations of

Table 3. Concentration of mineral elements under different N rates and sampling dates in switchgrass bales during 2011–2012.

		B				Ca				Fe		
Sampling date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
		mg kg^{-1}				mg kg^{-1}				mg kg^{-1}		
3 Nov. 2011	0.31a	0.32a†	0.32a	0.29a	5.5ab	5.9a	5.1ab	5.5ab	0.11ab	0.12a	0.10a	0.11ab
8 Dec. 2011	0.31a	0.31a	0.32a	0.31a	5.9a	5.8a	6.4a	5.4ab	0.18ab	0.13a	0.12a	0.10ab
6 Jan. 2012	0.31a	0.34a	0.30a	0.29a	5.8ab	5.9a	5.7ab	5.7a	0.13a	0.13a	0.13a	0.13a
13 Feb. 2012	0.31a	0.32a	0.30a	0.32a	5.4ab	5.5a	5.7ab	5.1b	0.11ab	0.13a	0.11a	0.08b
19 Mar. 2012	0.32a	0.30a	0.33a	0.33a	5.2b	5.8a	4.3b	5.4ab	0.12ab	0.11a	0.13a	0.11ab
10 Apr. 2012	0.31a	0.32a	0.30a	0.32a	5.7ab	5.7a	5.6ab	5.9a	0.11b	0.10a	0.11a	0.11ab
18 May 2012	0.31a	0.32a	0.30a	0.31a	5.8ab	5.8a	5.8ab	5.6ab	0.10b	0.10a	0.10a	0.10ab
						Analysis of variance *P* > *F*						
N rate		0.55				0.42				0.25		
Time		0.96				0.36				0.18		
N rate × Time		0.60				0.46				0.60		
		K				Mg				Mn		
Sampling date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
		mg kg^{-1}				mg kg^{-1}				mg kg^{-1}		
3 Nov. 2011	7.4ab	6.5c	7.4ab	8.3a	5.2a	3.1b	3.4a	3.2a	0.05a	0.07a	0.04a	0.05a
8 Dec. 2011	8.1a	9.1a	7.8a	7.3a	3.3a	3.5a	3.3a	3.2a	0.05a	0.04a	0.07a	0.05a
6 Jan. 2012	7.2ab	7.7abc	5.5c	8.5a	3.2a	3.4ab	3.1a	3.2a	0.06a	0.04a	0.07a	0.05a
13 Feb. 2012	7.2ab	8.2ab	6.4bc	6.8a	3.0a	3.1b	3.1a	2.9a	0.04a	0.03a	0.05a	0.04a
19 Mar. 2012	7.6ab	8.7ab	7.1ab	7.1a	3.1a	3.3ab	3.0a	3.0a	0.04a	0.05a	0.05a	0.03a
10 Apr. 2012	6.7b	6.6c	6.7abc	6.9a	3.0a	3.0b	3.1a	3.0a	0.03a	0.03a	0.03a	0.04a
18 May 2012	7.1ab	7.4bc	6.9ab	6.9a	2.9a	3.0b	3.0a	3.0a	0.06a	0.08a	0.03a	0.04a
						Analysis of variance *P* > *F*						
N rate		0.018				0.41				0.48		
Time		0.17				0.44				0.50		
N rate × Time		0.02				0.51				0.19		
		Na				P				S		
Sampling date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
		mg kg^{-1}				mg kg^{-1}				mg kg^{-1}		
3 Nov. 2011	0.36ab	0.43a	0.34b	0.33a	1.4a	1.6a	1.4a	1.5a	0.65a	0.72a	0.53b	0.71a
8 Dec. 2011	0.38ab	0.40ab	0.38ab	0.35a	1.5a	1.3bc	1.6a	1.4a	0.67a	0.64ab	0.80a	0.57a
6 Jan. 2012	0.37ab	0.42ab	0.36ab	0.34a	1.4a	1.4abc	1.5a	1.3a	0.64a	0.56b	0.75a	0.61a
13 Feb. 2012	0.34b	0.38abc	0.32b	0.32a	1.5a	1.2c	1.6a	1.5a	0.64a	0.61ab	0.74a	0.56a
19 Mar. 2012	0.4a	0.37abc	0.43a	0.39a	1.5a	1.4abc	1.6a	1.5a	0.63a	0.54b	0.75a	0.61a
10 Apr. 2012	0.34b	0.35bc	0.34b	0.32a	1.5a	1.6a	1.5a	1.5a	0.59a	0.60ab	0.59b	0.58a
18 May 2012	0.34b	0.33c	0.34b	0.35a	1.5a	1.5abc	1.5a	1.5a	0.60a	0.59b	0.61b	0.60a
						Analysis of variance *P* > *F*						
N rate		0.02				0.87				0.008		
Time		0.04				0.44				0.39		
N rate × Time		0.33				0.05				0.002		

† Concentration values represent means of four replicates. Same letters in the same column for the same N treatment means no significant differences; different letters in the same column for the same N treatment means significant differences. There were no significant differences in the concentrations of elements among the three rates of N.

hemicellulose, cellulose, lignin, mineral elements, and N were lower in the second season than in the first season. Generally, during the storage time of the biomass of the first and second seasons, concentrations of the fiber constituents such as hemicellulose and cellulose in bales increased with increasing the storage time, which is good for the biomass feedstock quality. On the other hand, the concentrations of lignin, mineral elements, and N increased, which may reduce the quality of the biomass feedstock as a bioenergy source.

Although the feedstock quality generally increased, the biomass decreased in the first season, but remained relatively steady in the second season during the storage period (data not shown). If the loss of the biomass is significant, that may lead to a profit loss even though the quality increased. Consequently, switchgrass producers may need to evaluate storage options and weather conditions to improve yield of switchgrass stored in bales, particularly in areas with high winter and spring precipitation.

Biomass Quality of Standing Switchgrass

Harvest time has an important impact on the quality of switchgrass biomass feedstock. In addition, optimal quality varies depending on the conversion technique used to generate energy (Liu et al., 2015). Generally, we found no significant differences in the concentrations of fiber constituents among N rates within each sampling date (Table 1). Delaying harvest of switchgrass from December 2010 to May 2011 (the first season) and from December 2011 to May 2012 (the second season) significantly reduced the concentration of hemicellulose (Table 1). For example, under the rate of 56 kg N ha^{-1}, hemicellulose significantly decreased by 8% from 264 to 244 g kg^{-1} (during the first season, stand 2010–2011), and by 9% from 236 to 215 g kg^{-1} (during the second season, stand 2011–2012) (Table 1). In contrast, under all of the N rates, cellulose concentration significantly increased from December to May (e.g., its concentration under the rate of 56 kg N ha^{-1} increased by 4%, from 389 to 407 g kg^{-1}; and by 7% from 390 to 420 g kg^{-1} during the first and second seasons, respectively) (Table 1). These results revealed that quality of the switchgrass biomass generally increased by delaying the harvest time. The increase in the fiber constituents make the switchgrass desirable for biofuel production (Bates, 2008).

The concentrations of mineral elements (e.g., Ca, K, Mg, Na, P, and S) affect the quality of switchgrass biomass feedstock as a source of bioenergy, that is, low concentrations of these elements increase the feedstock quality especially when converting the biomass to energy via direct combustion (Adler et al., 2006). Table 4a shows that the mineral elements concentrations generally decreased by delaying the harvest time. In addition, during the first season (2010–2011), these elements differed from each other in their concentrations, which could be ranked as: Ca > Na > *P* > K > Mg. Under the rate of 112 kg N ha^{-1}, the Ca concentration generally decreased although with no significant differences from December 2010 to May 2011 (Table 4). Potassium concentration, however, drastically decreased under all of the N rates, for example, it decreased by 67% (from 4.5 to 1.5 g kg^{-1}) from December 2010 to May 2011, under the 56 kg N ha^{-1}. Similarly, Mg concentration decreased by 30% (from 2.7 to 1.9 g kg^{-1}) under the rate of 56 kg N ha^{-1}. The rest of the elements decreased slightly

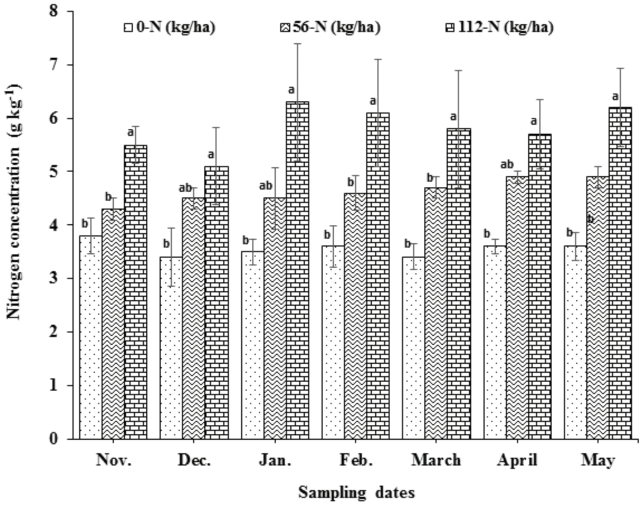

Fig. 2. Nitrogen content in switchgrass biomass bales as affected by sampling dates and N rates in the second season (2011–2012). Error bars represent standard deviation. The same letters shown in bars within each month indicates no significant difference.

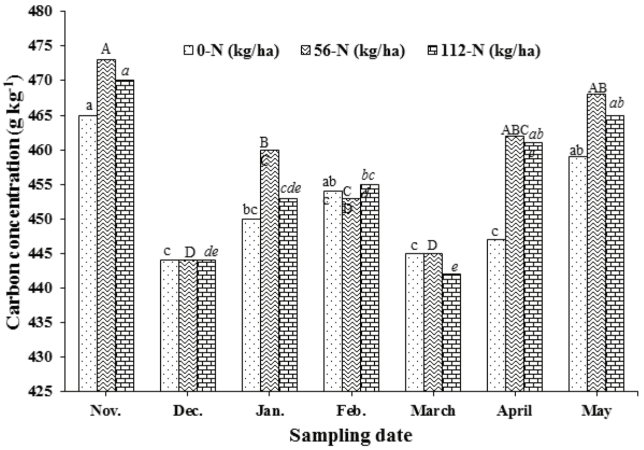

Fig. 3. Carbon concentration in switchgrass biomass bales as affected by sampling dates and N rates during the first season (2010–2011). Error bars represent standard deviation. No significant differences were found in C concentrations under the three N rates.

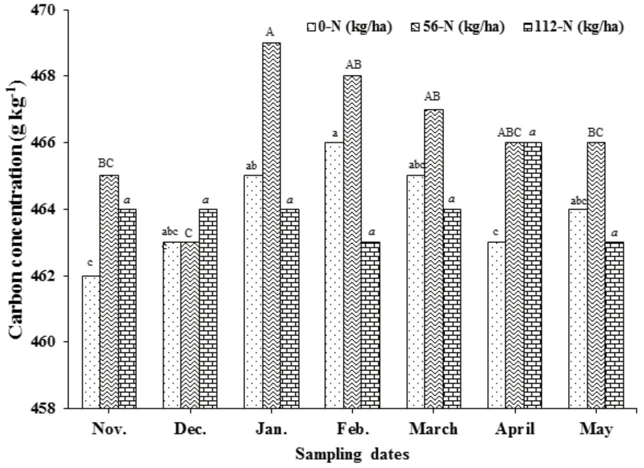

Fig. 4. Carbon concentration in switchgrass biomass bales as affected by sampling dates and N rates during the second season (2011–2012). Error bars represent standard deviation. There were no significant differences between C concentrations under the three N rates.

(e.g., Fe, Mn, P, and S) or increased (e.g., B and Na) (Table 4a). Similar results for these mineral elements were found in Pennsylvania by Adler et al. (2006). In the second season (2011–2012), concentrations of all of the mineral elements significantly decreased from December 2011 to May 2012. For example, mineral concentrations decreased by 14, 38, 10, 98, 46, 25, 70, 21, and 48% for B, Ca, Fe, K, Mg, Mn, Na, P, and S, respectively (Table 4b).

Compared to concentrations of all of the mineral elements in the first season (2010–2011), their concentrations (except K) during the second season (2011–2012) were generally lower and may be because switchgrass encountered drier conditions in 2011 than in 2010, which may have limited the uptake of nutrients. Potassium concentration in the delayed harvest biomass in the second season was higher than that of the first season because the drier conditions may have induced switchgrass to take up more K to be able to tolerate drought (Egilla et al., 2001).

Compared with N concentrations in the baled switchgrass biomass during the first and second seasons (Fig. 1 and 2), N concentrations in the delayed harvest biomass (Table 5) tended to decline, which could be ascribed to the translocation of N from the shoots to the rhizomes and roots after maturity (Heckathorn and Delucia, 1996) and to leaf loss from standing switchgrass. Nitrogen concentrations in the delayed harvest switchgrass did not significantly change during the first season (2010–2011) (Table 5). However, its concentrations significantly changed during the second season (2011–2012), but there was no clear trend of that change (Table 5). For example, under the rate of 56 kg N ha^{-1} the N concentration was 2.7, 2.5, and 2.6 g kg^{-1} in December 2011, February 2012, and May 2012, respectively. Similarly, during the first (2010–2011) and second (2011–2012) seasons, C concentration did not change significantly (Table 5). Further, C concentrations were not significantly different among N rates in each separate month. Generally, delaying harvest time increased the quality of switchgrass biomass by reducing the concentrations of lignin, mineral elements, and N, and increasing the concentration of cellulose (Johnson and Gresham, 2014).

The yield of standing switchgrass for the two growing seasons is summarized in Table 6. For the first season (2010– 2011), average yield between Dec. 2010 and May 2011 decreased significantly, while there was not a significant difference within a N rate. For the second season (2011–2012), it was observed that yield decreased significantly across all N rates. This may be due to the drier conditions during the second growing season and increased shattering of dry, standing plants. A study conducted by Adler et al. (2006) showed similar results with regard to reduction in yield when harvest

Table 4a. Impact of harvest time and N rate on the concentration of mineral elements in standing switchgrass during 2010–2011.

		B				Ca				Fe		
Harvest date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
		———	mg kg^{-1}	———		———	mg kg^{-1}	———		———	mg kg^{-1}	———
7 Dec. 2010	0.43a	0.42a	0.44a	0.42a	8.8a	9.4a	7.8a	9.0a	0.23a	0.24a	0.22a	0.22a
21 Apr. 2011	0.42a	0.45a	0.40a	0.43a	8.1a	8.4a	7.9a	7.8a	0.24a	0.24a	0.23a	0.24a
11 May 2011	0.44a	0.43a	0.45a	0.45a	8.0a	7.3a	9.1a	7.7a	0.26a	0.22a	0.31a	0.26a
						Analysis of variance $P > F$						
N rate	0.86				0.97				0.61			
Time	0.28				0.64				0.34			
N rate × Time	0.10				0.55				0.43			
		K				Mg				Mn		
Harvest date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
		———	mg kg^{-1}	———		———	mg kg^{-1}	———		———	mg kg^{-1}	———
7 Dec. 2010	4.0a	3.4a	4.5a	4.1a	3.0a	3.1a	2.7a	3.3a	0.08a	0.10a	0.07a	0.08a
21 Apr. 2011	1.7b	1.3b	1.7b	2.0b	2.2b	2.1b	2.2ab	2.3b	0.07a	0.06b	0.09a	0.07a
11 May 2011	1.4b	1.2b	1.5b	1.3c	1.9b	2.0b	1.9b	2.0b	0.07a	0.08ab	0.08a	0.07a
						Analysis of variance $P > F$						
N rate	0.07				0.39				0.75			
Time	<0.0001				<0.0001				0.74			
N rate × Time	0.68				0.63				0.69			
		Na				P				S		
Harvest date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
		———	mg kg^{-1}	———		———	mg kg^{-1}	———		———	mg kg^{-1}	———
7 Dec. 2010	6.9b	6.8b	7.0a	7.1a	6.0a	6.8a	6.3a	4.9a	1.4a	1.4a	1.4a	1.3a
21 Apr. 2011	7.2ab	8.1a	6.7a	6.8a	5.2a	5.5a	5.1a	5.0a	1.2b	1.2b	1.1b	1.2a
11 May 2011	7.9a	8.0a	6.7a	7.8a	5.2a	5.1a	5.5a	4.9a	1.2b	1.2b	1.3ab	1.2a
						Analysis of variance $P > F$						
N rate	0.55				0.38				0.73			
Time	0.0486				0.38				0.006			
N rate × Time	0.43				0.83				0.68			

† Concentration values represent means of four replicates. Same letters in the same column for the same N treatment under the same season means no significant differences; different letters in the same column for the same N treatment means there are significant differences. No significant differences were found among N rates in each separate month.

was delayed from autumn to the following spring. When determining optimum harvest timing, the economic costs related to the reductions in yield must be taken into consideration in conjunction with the increased quality aspects of delaying switchgrass harvest from late autumn to the following spring.

CONCLUSIONS

Storing switchgrass biomass in round bales for 7 mo slightly increased the concentrations of cellulose and hemicellulose, which is desirable for the biomass quality; however, the changes were not consistent. Also, storage of switchgrass biomass increased the concentrations of lignin, mineral elements, and N, which is not desirable for biomass quality. Although the feedstock quality increased, the biomass decreased through the storage period. If the loss of biomass is significant, that may lead to a profit loss even though the quality increased. Consequently, storage conditions must be considered both in terms of yield and quality. Delaying harvest time from fall to spring increased switchgrass biomass quality through increasing the concentrations of cellulose and reducing the concentrations of mineral elements and N. Generally, the concentrations of all of the fiber constituents, mineral elements, and N were lower in the delayed harvest biomass compared with those stored in bales. However, yield was also reduced when stored

Table 4b. Impact of harvest time and N rate on the concentration of mineral elements in standing switchgrass during 2011–2012.

		B				Ca				Fe		
Harvest date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
			mg kg^{-1}				mg kg^{-1}				mg kg^{-1}	
8 Dec. 2011	0.37ab	0.40a	0.36ab	0.35ab	5.2a	5.3a	5.0ab	5.2a	0.21a	0.24a	0.19a	0.22a
6 Jan. 2012	0.40a	0.40a	0.42a	0.36a	5.4a	5.3a	5.6a	5.4a	0.19a	0.22ab	0.18a	0.18ab
13 Feb. 2012	0.38ab	0.39a	0.36ab	0.39a	4.3b	4.3bc	4.2abc	4.4b	0.17ab	0.16bc	0.18a	0.17ab
19 Mar. 2012	0.35bc	0.37a	0.33b	0.36a	4.5b	4.9ab	4.2abc	4.3b	0.15b	0.14c	0.14a	0.17ab
10 Apr. 2012	0.33cd	0.34ab	0.32b	0.32ab	4.1bc	4.4bc	3.9bc	3.9b	0.14b	0.14c	0.17a	0.12b
18 May 2012	0.29d	0.28b	0.31b	0.29b	3.6c	3.8c	3.1c	3.9b	0.17ab	0.15c	0.17a	0.18ab
						Analysis of variance *P* > *F*						
N rate			0.32				0.35				0.96	
Time			<0.0001				<0.0001				0.02	
N rate × Time			0.63				0.97				0.43	
			K				Mg				Mn	
Harvest date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
			mg kg^{-1}				mg kg^{-1}				mg kg^{-1}	
8 Dec. 2011	5.7a	5.8a	5.8a	5.6a	2.6a	2.9a	2.6a	2.4a	0.04a	0.04a	0.04a	0.03a
6 Jan. 2012	4.7b	4.8a	5.1a	4.3b	2.3b	2.3b	2.1b	2.5a	0.04a	0.05a	0.04a	0.03a
13 Feb. 2012	3.3c	2.8b	3.3b	3.9b	1.8c	1.8c	1.8b	1.8b	0.02b	0.03a	0.01b	0.03a
19 Mar. 2012	3.1c	2.7b	3.4b	3.3b	2.3b	2.4b	2.0b	2.4a	0.03ab	0.02a	0.03ab	0.02a
10 Apr. 2012	1.9d	1.7bc	2.2b	1.8c	2.1b	2.3b	1.9b	2.2ab	0.03ab	0.02a	0.03ab	0.02a
18 May 2012	0.4e	1.1c	0.1c	0.05d	1.6c	1.5c	1.4c	1.9b	0.03ab	0.02a	0.03ab	0.02a
						Analysis of variance *P* > *F*						
N rate			0.76				0.004				0.29	
Time			<0.0001				<0.0001				0.11	
N rate × Time			0.36				0.22				0.42	
			Na				P				S	
Harvest date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N	Avg.	0-N	56-N	112-N
			mg kg^{-1}				mg kg^{-1}				mg kg^{-1}	
8 Dec. 2011	1.1b	1.1b	1.1a	1.0b	0.61c	0.51d	0.81b	0.67a	0.61a	0.61a	0.67a	0.55a
6 Jan. 2012	1.1b	1.2ab	1.2a	1.1ab	0.78ab	0.71c	1.1a	0.53a	0.53ab	0.53ab	0.60ab	0.47ab
13 Feb. 2012	1.2a	1.3a	1.1a	1.2a	0.68bc	0.72c	0.65b	0.69a	0.51bc	0.54ab	0.55ab	0.45ab
19 Mar. 2012	0.5c	0.53c	0.52b	0.55c	0.82ab	0.99ab	0.84b	0.64a	0.45bcd	0.52ab	0.45bc	0.39b
10 Apr. 2012	0.4d	0.40d	0.45b	0.39d	0.85a	1.10a	0.87b	0.61a	0.44cd	0.52ab	0.43bc	0.36b
18 May 2012	0.3e	0.32e	0.33c	0.36d	0.77ab	0.83bc	0.64b	0.68a	0.37d	0.41b	0.35c	0.36b
						Analysis of variance *P* > *F*						
N rate			0.81				<0.0001				0.0049	
Time			<0.0001				0.0005				<0.0001	
N rate × Time			0.6				<0.0001				0.76	

† Concentration values represent means of four replicates. Same letters in the same column for the same N treatment under the same season means no significant differences; different letters in the same column for the same N treatment means there are significant differences. No significant differences were found among N rates in each separate month.

Table 5. Impact of harvest time and N rate on the concentration of N and C in standing switchgrass during 2010–2011 and 2011–2012.

	N				C			
Harvest date	Avg.	0-N†	56-N	112-N	Avg.	0-N	56-N	112-N
			g kg^{-1}				g kg^{-1}	
2010–2011								
7 Dec. 2010	4.2a	4.2a‡	3.8a	4.6a	459b	459ab	461a	457b
21 Apr. 2011	4.2a	4.3a	4.1a	4.3a	465ab	457b	467a	471a
11 May 2011	4.5a	4.2a	4.5a	4.6a	469a	467a	466a	473a
			Analysis of variance *P* > *F*					
N rate			0.22				0.21	
Time			0.35				0.02	
N rate × Time			0.54				0.27	
2011–2012								
8 Dec. 2011	2.8ab	2.2bc	2.7ab	3.4a	472b	471a	471a	472b
6 Jan. 2012	2.3c	2.1c	2.2b	2.6b	474a	474a	474a	476a
13 Feb. 2012	2.4bc	2.4abc	2.5ab	2.5b	472b	471a	471a	474ab
19 Mar. 2012	2.5abc	2.2bc	2.7ab	2.6b	473ab	470a	473a	476a
10 Apr. 2012	2.9a	2.9a	3.0a	2.9ab	472ab	470a	473a	474ab
18 May 2012	2.7abc	2.8ab	2.6ab	2.7ab	473ab	471a	472a	476a
			Analysis of variance *P* > *F*					
N rate			0.11				0.0005	
Time			0.04				0.15	
N rate × Time			0.10				0.88	

† Nitrogen treatments rates were 0, 56, and 112 kg N ha^{-1}.

‡ Same letters in the same column for the same N treatment under the same season means no significant differences; different letters in the same column for the same N treatment means there are significant differences. No significant differences between either N concentrations, or C concentrations were found among the N rates in each separate month.

unharvested in the field. Results from this study indicate that delaying switchgrass harvest may improve feedstock quality for bioenergy in certain types of systems; however, yield losses should also be considered when storing switchgrass, either in bales on uncut in the field.

Table 6. The yield response to delayed harvesting of switchgrass during two seasons (2010–2011 and 2011–2012).

	Biomass yield			
Harvest date	Avg.	0-N†	56-N	112-N
		Mg ha^{-1}		
2010–2011				
7 Dec. 2010	11.2a	9.0a‡	10.6a	13.9a
11 May 2011	8.5b	7.8a	8.5a	9.1a
		Analysis of variance *P* > *F*		
N rate		0.045		
Time		0.01		
N rate × Time		0.283		
2011–2012				
8 Dec. 2011	13.2a	12.4a	13.2a	14.0a
18 May 2012	4.9b	5.2b	4.3b	5.4b
		Analysis of variance *P* > *F*		
N rate		0.46		
Time		<0.0001		
N rate × Time		0.54		

† Nitrogen treatments rates were 0, 56, and 112 kg N ha^{-1}.

‡ Same letters in the same column during the same season for the same N treatment means no significant differences.

ACKNOWLEDGMENTS

This research was supported by funding from the North Central Regional Sun Grant Center at South Dakota State University through a grant provided by the U.S. Department of Energy Bioenergy Technologies Office under award number DE-FC36-05GO85041.

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