Switchgrass Winter Yield, Year-Round Elemental Concentrations, and Associated Soil Nutrients in a Zero Input Environment

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ABSTRACT

The maximum biomass yield of switchgrass (*Panicum virgatum* L.) usually is achieved with one seasonal autumn harvest. However, information is limited on the influences of winter harvesting on annual biomass yield and on quality parameters impacting conversion into bioethanol. Accordingly, the objectives of this study were to assess: (i) yield of standing field cured biomass at monthly intervals through winter, (ii) year-round elemental composition of biomass, and (iii) associated year-round soil nutrient status. An unfertilized 'Kanlow' switchgrass planting established in 1998 was used for this study conducted from November 2007 to October 2010. The experimental treatment was monthly harvest from November to the following March and year-round monthly sampling of biomass (except April) and soil for chemical analyses. The 3-yr mean dry matter yield of winter harvests was 5.94Mg ha^{-1}, ranging from 3.88 Mg ha^{-1} in the winter of 2007–2008 to 7.55 Mg ha^{-1} in 2009–2010. Monthly biomass yield differences were significant in Years 1 and 3 but not in Year 2. Concentrations of biomass elements and soil nutrients changed with various degrees over the 3 yr. Concentrations of ash, cell wall components, and mineral nutrients, except P, K, and S, did not change appreciably across winter months. Early winter harvests resulted in less yield loss compared to late winter harvests. These findings will be valuable in harvest management for switchgrass biomass production.

Switchgrass is a warm-season perennial grass native to North America. It is considered a leading candidate for deployment as a cellulosic biomass feedstock crop for bioenergy production (U.S. Department of Energy, 2011). The species has high potential to be cultivated as a renewable biofuels feedstock source on marginal land unsuited for traditional cultivated grain and forage crops (Parrish and Fike, 2005). Switchgrass is comprised of two major ecotypes designated "lowland" and "upland" based on edaphic adaptation and plant morphology. Native stands of the lowland ecotype occur on alluvial soils while native stands of the upland ecotype are typically found on drier and less fertile nonalluvial soils. The lowland ecotype is naturally distributed in the south-central and southeastern United States to about 40° N latitude while the upland ecotype is distributed throughout the expanse of U.S. switchgrass adaptation. Plants of the lowland ecotype are typically much larger than those of the upland ecotype, thereby having greater biomass production potential in suitable growth environments. Deployment of switchgrass as a bioenergy feedstock crop in the south-central and southeastern United States would likely heavily use lowland cultivars because of their greater biomass production potential compared to upland cultivars.

Harvest timing is an important consideration in switchgrass production management as it affects biomass yield, chemical composition, harvesting cost, and stand persistence. Sanderson et al. (1999) reported that maximum biomass yield of lowland switchgrass was achieved in Texas with one seasonal autumn harvest completed by mid-September. They further noted total yield was reduced by 12 to 19% depending on locations when the one seasonal harvest was taken in November compared with September. However, delaying the harvest past October in a one-cut system can help maximize switchgrass biomass production the next year (Sanderson et al., 1999). Casler and Boe (2003) measured the effects of a single seasonal harvest of six upland switchgrass cultivars in Wisconsin and South Dakota during August, September, and October. They reported that an August harvest produced the largest biomass yield in the first year, but proved detrimental to biomass yield and stand persistence by the third year of the study. They further indicated that an October harvest produced the greatest biomass yields over a 4-yr period.

Parrish et al. (1997) reported decreased biomass yields associated with delaying autumn harvest of lowland switchgrass in Virginia. The decrease in biomass yield associated with delayed autumn harvest has been attributed partially to the remobilization and translocation of C and N reserve compounds from aboveground biomass to regenerative crown structures and underground roots (Parrish et al., 1997; Sanderson et al., 1999). Leaf loss near and after the end of the growing season is also thought to contribute to biomass yield reduction (Parrish et al., 1997; Sanderson et al., 1999). Although early fall harvest is recommended (Sanderson et al., 1999), a wider window extending harvest into or through winter months would alleviate potential problems associated with the much shorter early

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Abbreviations: ADF, acid detergent fiber; ADL, acid detergent lignin; EW, early winter; LW, late winter; NDF, neutral detergent fiber; OM, organic matter.

fall window. Therefore, it becomes imperative to study yield performance in delayed harvests in winter months.

Date of harvest also influences the chemical compositions of aboveground and belowground biomass of switchgrass. Preservation of carbohydrate reserves associated with harvesting near or after end of growing season can help to reduce plant mortality and maintain stand stability in more northern locations (Casler and Boe, 2003). Delaying harvest until spring resulted in a decrease in yield and mineral concentrations of biomass in upland switchgrass cultivars (Adler et al., 2006). Yield losses were attributed mainly to harvest losses. The decrease in minerals in switchgrass aboveground biomass is considered beneficial to the conversion into bioethanol and in maintaining soil fertility. Adler et al. (2006) stated that spring-harvested biomass with decreased mineral concentrations could improve combustion quality of the biomass compared to fall-harvested biomass. Delayed harvest increased dry matter content and neutral detergent fiber (NDF) concentration, while the ash concentration decreased (Casler and Boe, 2003). Biomass with higher NDF content and lower acid detergent fiber (ADF) and lignin content would be beneficial for increasing fermentable sugars and decreasing unfermentable and/or uncombustible residues (Casler and Boe, 2003). Yang et al. (2009) observed that the concentrations of N, P, and K decreased in the shoots of switchgrass accessions in late December harvest compared to the August harvest. Appropriate procedures of harvest management can maximize long-term biomass yield and maintain appropriate chemical contents; that is, low level of moisture and ashes in the biomass for biofuels (Monti et al., 2008).

Harvest timing also has economic consequences relative to feedstock storage, physical and chemical changes of stored feedstock, and equipment. Large-scale industrial biofuel production requires a continuous supply of feedstock necessitating storage of the feedstock near conversion facilities (Agblevor et al., 1995). Long-term storage may result in mechanical loss and biochemical degeneration of the feedstock (Agblevor et al., 1995). Delaying feedstock harvest to winter months would reduce on-site storage time. Mapemba et al. (2008) point out that a short harvest interval will require more labor and energy compared to a longer interval. Hwang et al. (2009) studied short (October–December) vs. extended (July–February) switchgrass harvest intervals as they influence logistics of harvest and storage in Oklahoma. They found that an extended harvest season could reduce the cost of harvest machines and feedstock delivery compared to the short harvest season (Hwang et al., 2009).

Vogel et al. (2002) reported that N is the major fertilizer input and represents a major portion in the cost of switchgrass production. Therefore, production practices that reduce N requirement while maintaining economic biomass yield could enhance profitability; however, further economic analyses are needed to confirm the profitability of specific production practices (Vogel et al., 2002). Depletion of soil nutrients with biomass production can be reduced by delaying harvest (Yang et al., 2009). Yang et al. (2009) reported 'Kanlow' switchgrass is efficient in nutrient use, in terms of less N and P per unit of biomass in senescent shoots compared to upland cultivars. Haque et al. (2009) found maximum expected net return from switchgrass biomass yield was achieved with 65 kg N ha^{-1} with one post-senescence harvest per year for most biomass price and N cost combinations in Oklahoma. In another study, optimum biomass yields were obtained when upland switchgrass was harvested at full panicle emergence from the boot stage to post-anthesis when 120 kg N ha^{-1} of fertilizer was applied (Vogel et al., 2002). Heggenstaller et al. (2009) found that switchgrass shoot biomass was affected by N rate and year. They obtained highest yield at 220 kg N ha^{-1}; however, biomass yield return on incremental N beyond 140 kg N ha^{-1} was negligible. Hence, they recommended about 140 kg N ha^{-1} or slightly greater as the optimum N input for Central Iowa with precise recommendation dependent on N and biomass costs. Their study also found that active shoot to root translocation of P and K was negligible compared to N at the time of harvest. Similarly, Muir et al. (2001) reported the application of 168 kg N ha^{-1} yr^{-1} could help to avoid decline in biomass yield over the years in central Texas. Lowenberg-DeBoer and Cherney (1989) surmised that no or low N fertilization and harvest of mature forage would maximize returns and be risk efficient for switchgrass biomass production. Information on biomass yield and N outputs from biomass harvested during winter in a zero input scenario is not available, and this information would provide a baseline for future economic analyses.

Harvest delay until winter months is useful in terms of economic use of harvest machines and in reducing storage quantity of biomass. Winter harvest can provide a wider harvest window which is needed to harvest large areas, provide producers an opportunity to gain from potential increases in off-season market price, and enable a large-scale industrial biorefinery to have sustained year-round supply of feedstocks. However, information is limited on winter biomass yield, elemental composition of standing cured biomass, and associated soil nutrient status in switchgrass grown in the central United States, which is predicted to be a major region for switchgrass feedstock production (U.S. Department of Energy, 2011). Accordingly, the objectives of this study were to assess for Kanlow switchgrass: (i) yield of standing field cured biomass at monthly intervals through winter, (ii) year-round elemental composition of biomass, and (iii) associated year-round soil nutrient status.

MATERIALS AND METHODS

Experimental Site and Design

This study was conducted at the Oklahoma State University Agronomy Research Station in Stillwater, OK (36°8′ N, 97°63′ W). The soil was an Easpur loam (fine-loamy, mixed, superactive, thermic Fluventic Haplustolls). The weather and climate data are presented in Tables 1, 2, and 3.

A 'Kanlow' switchgrass planting established in 1998 was used for the study. 'Kanlow' switchgrass is a lowland cultivar developed and released in 1963 by the Kansas Agricultural Experiment Station and the Plant Science Division of the USDA-ARS, using germplasm originated in Oklahoma. The switchgrass field was not fertilized or supplied with any nutrients or pesticides for 6 yr (3 yr before the beginning of the study and 3 yr during the study period from November 2007 through October 2010). In Stillwater, the growing season for switchgrass usually occurs from April to October. In this paper, we define winter months as November to March and growing season as April through October.

Table 1. Monthly average of the mean daily temperature at Stillwater, OK, from 2007 to 2010 compared with 30-yr average (1971–2000).†

Month	2007	2008	2009	2010	30-yr mean
	air temperature, °C				
January	1.2	3.1	1.6	0.7	1.4
February	4.1	3.7	8.3	1.7	4.4
March	14.7	10.2	11.6	9.5	9.6
April	13.3	14.3	15.2	17.1	14.9
May	20.7	20.6	19.2	19.9	20.1
June	23.6	25.5	27.2	26.9	25.0
July	26.1	27.9	27.2	27.7	27.9
August	28.3	26.3	25.3	28.2	27.4
September	23.0	21.1	20.7	23.3	22.7
October	17.2	15.2	12.4	16.5	16.3
November	10.0	9.3	11.6	10.1	9.3
December	2.5	3.1	0.9	3.3	3.6

† Source: www.mesonet.org/index.php/weather/station_monthly_summaries and http://ggweather.com/normals/OK71.htm.

Table 2. Monthly total precipitation at Stillwater, OK, from 2007 to 2010 compared with 30-yr average (1971–2000).†

Month	2007	2008	2009	2010	30-yr mean
	precipitation, cm				
January	3.4	1.4	0.4	2.6	3.3
February	1.1	6.6	5.3	6.8	4.1
March	13.9	10.5	9.2	4.2	8.2
April	10.5	14.6	12.9	9.2	8.8
May	26.5	16.2	8.3	18.1	13.7
June	42.5	12.5	4.4	13.9	11.0
July	17.8	12.7	12.6	11.2	6.8
August	3.3	3.4	19.1	6.4	7.7
September	11.7	4.2	7.8	7.1	10.5
October	8.4	5.3	18.4	4.4	8.2
November	2.2	6.5	3.9	4.9	6.5
December	2.7	2.3	1.4	1.3	4.4

† Source: www.mesonet.org/index.php/weather/monthly_rainfall_table/stil and http://ggweather.com/normals/OK71.htm.

Table 3. Monthly total solar radiation at Stillwater, OK, from 2007 to 2010.†

Month	2007	2008	2009	2010
	solar radiation, MJ m^{-2}			
January	8.50	9.58	10.32	8.29
February	12.10	11.38	14.54	9.49
March	14.20	15.69	14.85	14.30
April	17.58	19.96	17.81	19.81
May	16.71	23.14	20.44	20.21
June	18.21	23.19	25.09	24.53
July	22.38	23.67	23.29	23.47
August	22.19	18.73	22.82	23.34
September	16.45	16.86	14.84	18.76
October	14.29	14.16	10.29	15.78
November	10.81	11.58	9.77	11.19
December	6.51	8.21	7.90	8.16

† Source: www.mesonet.org/index.php/weather/station_monthly_summaries.

The experimental design was a randomized complete block design with six replications over 3 yr, with plots remaining in the same place each year. Each winter month constituted a harvest treatment. Each of these 30 plots (5 harvest months × 6 reps) measured 27.4 by 5.5 m. For the evaluation of year-round biomass elemental composition, forage quality constituents and soil nutrients, respective biomass samples and soil samples were taken in each month in the winter season and in May through October during the growing season. The month of April was not included because plants were just beginning to grow. Biomass and soil samples taken during the growing season were collected monthly from six plots located in the center of the field experiment that each measured 27.4 by 27.4 m. The growing season plots were completely harvested toward the end of November to prepare for the plants to regrow during the following year.

Sampling and Measurements

Biomass yields and samples were collected toward the end of each harvest/sampling month. In each winter month, fresh biomass yield for each of six replications was recorded after swathing and baling which were performed using a swather (John Deere MoCo–Model 630, John Deere Co., Moline, IL) and a baler (John Deere–Model 568, John Deere Co., Moline, IL). A digital load cell system attached to a tractor was used for weighing the bales. At the same time, random hand grabbed biomass samples of approximately 500 g were collected from each plot. Biomass samples were then weighed for fresh weight, dried at 55°C in a forced air oven for 3 to 7 d, and again weighed for dry weight. Dry matter percent was thus calculated.

In each growing season month, one aboveground biomass sample was randomly hand clipped from each of six plots. Fresh weight of each sample taken was approximately 1 kg. The biomass samples were then dried as described above. The dry biomass samples were ground to pass through a 1-mm sieve and were analyzed for total nitrogen (TN) P, K, Ca, Mg, Na, S, Fe, Zn, Cu, Mn, Ni, C, ash, ADF, NDF, and acid detergent lignin (ADL).

During winter months, soil samples were collected from the 30 winter biomass harvest plots immediately after harvest and biomass sample collection. During the growing seasons, soil samples were taken monthly from the six plots located near the center of the field experiment. Each soil sample was a mixing composite sample of 15 to 20 random cores collected from 0- to 15-cm depth with a soil probe that was 2.3 cm i.d. In summers when soil in the field was very dry, a soil drill was used to obtain the samples. The collected soil samples were analyzed for pH, NO$_3$–N, P, K, SO$_4$, Ca, Mg, Fe, Zn, B, Cu, and organic matter (OM).

Monthly records of daily rainfall data were retrieved from the Oklahoma Mesonet website (from November–March of the following year). Monthly accumulated rainfall up to the date of winter harvest was calculated for each of the months December, January, February, and March. Therefore, for the month of December, we used daily rainfall data after November harvest date up to the December harvest date. The same procedure was followed for the remaining months as well.

Forage Quality Analyses

Forage samples were collected and dried at 85°C overnight and ground to pass through a 1-mm screen. The moisture contents of the switchgrass samples were determined by drying ground samples at 105°C for 8 h. Total N was determined using a dry combustion nitrogen analyzer (Leco TruSpec CN, St. Joseph, MI) (Undersander et al., 1993). Acid detergent fiber and ADL were determined using an Ankom fiber analyzer (ANKOM

Table 4. Switchgrass dry biomass yield as affected by winter harvest month and year.

Harvest month	Year 1 (2007–2008)	Year 2 (2008–2009)	Year 3 (2009–2010)
		$Mg\ ha^{-1}$	
November	4.99	5.42	7.11
December	4.46	6.41	8.27
January	3.88	6.89	8.97
February	3.14	6.70	6.57
March	2.95	6.48	6.84
Effect			
Month	***	ns†	**
Contrast			
‡Early and late winter	***		**

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† ns, not significant ($P > 0.05$).

‡ Early winter includes November, December, and January; late winter includes February and March.

Technology, Macedon, NY). Mineral concentrations of the forage samples measured using a Spectro CirOs inductively coupled plasma instrument (SPECTRO Analytical Instruments Inc., Boschstr, Germany] following digestion (Undersander et al., 1993).

Soil Analyses

Soil samples were dried at 60°C overnight and ground to pass a 2-mm sieve. Soil pH and buffer index were measured by glass electrodes in a 1:1 soil/water suspension and Shoemaker, McLean, and Pratt (SMP) buffer solution, respectively (Sims, 1996). Soil NO_3–N was extracted with 1 M KCl solution and quantified by the Cd reduction method on a Lachat QuikChem 8000 (LACHAT, 1994). Soil available P, K, Ca, and Mg were extracted using Mehlich 3 solution (Mehlich, 1984). Phosphorus, K, Ca, and Mg in the extract were analyzed by a Spectro CirOs ICP (Soltanpour et al., 1996). Soil organic C was determined using a LECO Truspec dry combustion C analyzer (Nelson and Sommers, 1996). Soil SO_4 was extracted by 0.008 M $Ca_3(PO_4)_2$ and analyzed by a Spectro CirOs ICP. Plant available Zn, Fe, Cu, and B were extracted by DTPA-Sorbitol and quantified by ICP (Hanson et al., 1998). Soil texture was determined using the hydrometer method (Gee and Bauder, 1986).

Statistical Analyses

The data obtained on biomass yield, biomass chemical composition, and soil nutrients were analyzed using SAS version 9.2 (SAS Institute, 2008). Analysis of variance was performed using the MIXED procedure of SAS with month and year as fixed effects and block and interactions with block as random effects. Due to significant effects of year, year × month, or both for most measured variables, data were analyzed separately by year. Treatment means were separated using Fisher's Protected LSD ($P \leq 0.05$). The contrasts for early vs. late winter and early vs. late growing seasons were performed by assigning orthogonal coefficients in a SAS program. For the five winter months, we assigned orthogonal coefficients (2 2 2 −3 −3) which allowed us to compare the first three winter months with the last two winter months. For the growing season, we assigned orthogonal coefficients (1 1 1 −1 −1 −1) and compared the first three growing season months with the last three growing season months. The yield decrease in each successive winter month was calculated using the yield difference of the prior month and the present month. The data for decrease in yield and accumulated rainfall for the month were evaluated using the CORR procedure of SAS to determine if any correlation existed between the two.

Table 5. Significance levels for elemental concentrations of switchgrass biomass for different months.

Variable	Year	Winter month	Contrast (early vs. late winter)	Growing season month	Contrast (early vs. late growing season)
Total N	1	ns†		***	***
	2	ns		***	***
	3	ns		***	***
P	1	***	***	***	***
	2	***	***	***	***
	3	***	***	***	***
K	1	***	***	***	***
	2	***	***	***	***
	3	***	***	***	***
Ca	1	ns		**	***
	2	ns		ns	
	3	ns		ns	
Mg	1	***	***	*	**
	2	*	**	**	***
	3	ns		ns	
Na	1	**	***	**	ns
	2	ns	ns	**	**
	3	ns	ns	*	**
S	1	**	**	***	***
	2	*	**	***	***
	3	ns	**	***	***
Fe	1	ns		***	***
	2	**	**	***	***
	3	ns		ns	
Zn	1	ns		ns	
	2	ns		ns	
	3	ns		ns	
Cu	1	***	***	***	***
	2	***	*	***	***
	3	ns		*	**
Mn	1	ns		ns	
	2	ns		**	*
	3	ns		ns	
Ni	1	ns		***	ns
	2	ns		***	***
	3	ns		*	**
C	1	ns		***	***
	2	ns		***	***
	3	ns		*	**
Ash	1	ns		***	***
	2	ns		ns	
	3	ns		ns	
ADF‡	1	*	*	***	***
	2	ns		***	***
	3	ns		***	***
NDF	1	ns		***	***
	2	ns		***	***
	3	ns		***	*
ADL	1	ns		*	ns
	2	ns		***	***
	3	ns		***	***

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† ns, not significant ($P > 0.05$).

‡ ADF, acid detergent fiber; NDF, neutral detergent fiber; ADL, acid detergent lignin.

Table 6. Elemental concentrations of switchgrass biomass for different months.

		Month												
Variable	**Year**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**LSD**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**LSD**
Total N, %	1	0.30	0.34	0.32	0.31	0.30	0.06	1.10	0.68	0.51	0.35	0.35	0.25	0.10
	2	0.46	0.48	0.48	0.48	0.45	0.14	1.43	1.16	1.04	0.58	0.58	0.44	0.16
	3	0.23	0.25	0.27	0.24	0.22	0.70	0.90	0.73	0.68	0.36	0.36	0.30	0.20
P, %	1	0.10	0.07	0.05	0.05	0.05	0.02	0.23	0.15	0.12	0.11	0.11	0.08	0.03
	2	0.07	0.07	0.06	0.05	0.05	0.01	0.23	0.22	0.19	0.11	0.11	0.09	0.02
	3	0.08	0.08	0.06	0.05	0.05	0.01	0.20	0.17	0.13	0.12	0.12	0.11	0.05
K, %	1	0.31	0.15	0.12	0.08	0.06	0.05	1.87	1.24	0.77	0.59	0.59	0.38	0.16
	2	0.21	0.19	0.15	0.12	0.08	0.03	1.69	1.38	1.03	0.46	0.46	0.34	0.12
	3	0.26	0.21	0.13	0.09	0.09	0.04	1.23	1.14	0.79	0.46	0.46	0.35	0.31
Ca, %	1	0.21	0.24	0.22	0.21	0.21	0.04	0.21	0.19	0.19	0.16	0.16	0.14	0.03
	2	0.16	0.19	0.16	0.16	0.16	0.03	0.21	0.22	0.27	0.21	0.21	0.20	0.06
	3	0.16	0.2	0.20	0.18	0.17	0.05	0.20	0.20	0.18	0.18	0.18	0.19	0.04
Mg, %	1	0.18	0.15	0.13	0.13	0.10	0.03	0.19	0.18	0.19	0.13	0.13	0.13	0.05
	2	0.14	0.13	0.13	0.12	0.09	0.03	0.19	0.19	0.22	0.16	0.16	0.15	0.04
	3	0.12	0.13	0.13	0.11	0.10	0.03	0.15	0.15	0.14	0.14	0.14	0.14	0.03
Na, %	1	0.02	0.01	0.01	0.01	0.00	0.01	0.03	0.05	0.09	0.05	0.05	0.05	0.03
	2	0.01	0.02	0.02	0.01	0.01	0.01	0.04	0.03	0.02	0.02	0.02	0.02	0.01
	3	0.02	0.02	0.01	0.01	0.01	0.01	0.03	0.02	0.02	0.02	0.02	0.01	0.01
S, %	1	0.06	0.05	0.04	0.04	0.04	0.01	0.11	0.08	0.07	0.05	0.05	0.04	0.01
	2	0.04	0.05	0.04	0.04	0.04	0.01	0.11	0.10	0.10	0.06	0.06	0.05	0.02
	3	0.04	0.04	0.04	0.04	0.03	0.01	0.09	0.08	0.07	0.05	0.05	0.05	0.02
Fe, mg kg^{-1}	1	55	86	75	77	91	70	69	58	64	36	36	27	11
	2	48	65	54	67	62	9	69	90	103	66	66	76	12
	3	65	50	57	59	60	17	61	59	51	67	67	69	18
Zn, mg kg^{-1}	1	24	21	16	18	22	7	26	23	18	20	20	13	5
	2	18	21	17	18	18	3	29	31	31	22	22	20	5
	3	18	19	17	17	17	5	25	24	24	21	21	19	5
Cu, mg kg^{-1}	1	29	28	20	18	16	5	31	21	22	18	18	13	4
	2	12	14	10	12	10	2	16	22	25	13	13	15	3
	3	9	8	9	9	8	1	14	14	12	11	11	9	3
Mn, mg kg^{-1}	1	80	91	70	90	80	26	67	61	65	50	50	44	17
	2	49	52	43	52	46	11	101	76	69	67	67	74	18
	3	63	71	66	75	64	18	78	79	74	74	74	74	15
Ni, mg kg^{-1}	1	1.01	0.93	1.01	1.42	1.81	1.26	2.35	1.45	0.91	1.65	1.65	1.97	0.52
	2	0.25	0.28	0.20	0.21	0.17	0.08	1.43	1.15	0.98	0.32	0.32	0.26	0.29
	3	0.50	0.35	0.34	0.40	0.30	0.15	1.36	1.35	0.96	0.71	0.71	0.62	0.53
C, %	1	48	48	48	48	48	0	46	47	48	48	48	48	0
	2	49	49	49	49	49	2	47	47	47	48	48	48	1
	3	48	48	47	48	48	1	47	48	47	47	47	48	1
Ash, %	1	3	3	3	4	3	1	6	5	4	4	4	3	1
	2	3	3	3	2	3	0	2	2	2	2	2	3	0
	3	3	3	3	2	2	0	2	3	3	3	3	3	1
ADF†, %	1	50	50	52	51	53	2	38	41	50	50	50	52	2
	2	53	52	55	52	51	3	38	38	38	44	44	49	2
	3	51	51	51	51	52	2	35	42	41	44	44	48	2
NDF, %	1	65	65	68	67	67	3	56	58	63	64	64	65	2
	2	80	80	81	80	82	5	69	70	68	71	71	78	2
	3	82	81	82	82	84	2	69	75	72	72	72	76	3
ADL, %	1	9	9	9	9	9	1	9	7	9	8	8	8	1
	2	9	8	9	9	8	2	3	4	4	6	6	7	2
	3	8	8	8	8	8	1	2	4	5	7	7	8	1

† ADF, acid detergent fiber; NDF, neutral detergent fiber; ADL, acid detergent lignin.

RESULTS AND DISCUSSION

'Kanlow' switchgrass plants had no lodging during the three winters of the study, even though one or more heavy snow events occurred during each winter. Crop year, in general, had a significant impact on dry biomass yield, most biomass quality constituents and soil nutrients. There was significant interaction between year and harvest month for biomass yield.

Biomass Yield

The dry matter yield of winter harvests averaged over 3-yr was 5.94 Mg ha^{-1}, with minimum of 3.88 Mg ha^{-1} in 2007–2008 to maximum of 7.55 Mg ha^{-1} in 2009–2010. Monthly yield differences for winter biomass were significant in the Years 1 and 3, but not in the Year 2. In both Years 1 and 3, early winter [EW (November, December, and January)] yields were higher than late winter [LW (February and March)] yields (Table 4). The correlation analysis of yield and rainfall indicated no-consistent association of monthly yield decrease and accumulated monthly rainfall in winter for the three test winters. Vogel et al. (2002) stated that growing season rainfall was one of the likely causes of yield differences in cultivar Cave-in-Rock switchgrass in the Midwest. Rainfall along with its timing and amount can affect yield performance in switchgrass. Excessive growing season rainfall could correlate with very dense cloud cover and corresponding low levels of solar radiation, leading to reduced yield (Davis et al., 2008). May, June, July, and August are critical growth period for switchgrass and any sharp departure from normal rainfall and solar radiation events can

Table 7. Significance levels for soil pH, organic matter (OM), and soil chemicals in switchgrass field for different months.

Variable	Year	Winter month	Contrast (early vs. late winter)	Growing season month	Contrast (early vs. late growing season)
pH	1	ns†		ns	
	2	ns		ns	
	3	ns		ns	
NO_3–N	1	ns		***	**
	2	ns		*	*
	3	ns		***	***
P	1	ns		ns	
	2	ns		**	***
	3	ns		***	***
K	1	ns		ns	
	2	ns		***	*
	3	ns		ns	
SO_4	1	ns		*	ns
	2	ns		**	ns
	3	***	***	**	**
Ca	1	**	ns	ns	
	2	ns		ns	
	3	ns		ns	
Mg	1	**	ns	ns	
	2	ns		ns	
	3	ns		**	**
Fe	1	ns		ns	
	2	ns		*	ns
	3	ns		*	ns
Zn	1	ns		***	***
	2	ns		**	*
	3	ns		**	***
B	1	*	ns	ns	
	2	ns		ns	
	3	**	**	ns	
Cu	1	ns		ns	
	2	ns		*	ns
	3	ns		**	ns
OM	1	*	ns	ns	
	2	*	ns	ns	
	3	ns		ns	

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† ns, not significant (*P* > 0.05).

affect in plant growth. In our study, temperatures did not deviate excessively compared to 30-yr normal (Table 1). The rainfall in May and June was excessively higher for year 2007 compared to the 30-yr means (Table 2), which was also accompanied by lower total solar radiation (Table 3). The excessive rainfall and corresponding lower total solar rainfall could have caused reduced photosynthetic activities and corresponding lower yield in the first year. Winter yields were reduced in Year 1 relative to subsequent years up to a maximum of 41%.

Biomass Elemental Composition

The effect of year was significant for all elements in samples collected in winter months except for P and K. In winter, biomass N, Ca, Zn, Mn, Ni, C, ash, NDF, and ADL remained constant (Tables 5 and 6). Biomass P and K concentrations decreased significantly over winter months in each year, suggesting translocation of these elements to roots (Tables 5 and 6). Yang et al. (2009) reported that significant remobilization of P and K occurred from August to late December in a study conducted in southern Oklahoma. Our results of P and K indicated that these decline in concentration within biomass as the time progresses in winter. Biomass Mg concentration was higher in the EW compared to LW for Years 1 and 2, but was constant in Year 3. Biomass Na concentration was less in the LW period compared to the EW period in Year 1, but was constant during the winters of Years 2 and 3. In winter, there were no significant differences in Fe content for Years 1 and 3, but Fe concentrations increased during LW of Year 2. The Cu concentration was lower in LW compared to EW for Years 1 and 2 while Year 3 was constant for the winter Cu concentration. Although biomass ADF concentrations differed among the winter months for Year 1, the differences in Years 2 and 3 were not significant.

The year effect was significant for all the biomass elements studied except biomass C in growing seasons. Decreasing concentration of N, P, and K over the growing season months (Tables 5 and 6) was consistent with previous reports (Sanderson et al., 1999; Adler et al., 2006; Kering et al., 2011). Biomass Ca was higher in the early growing period compared to the late growing period for Year 1 whereas it was constant in Years 2 and 3 (Tables 5 and 6). Biomass Mg concentration was higher in the early growing period compared to the late growing period in Years 1 and 2. However, the biomass Mg was constant in Year 3. Biomass Na was different among growing months for each year. In Years 2 and 3 there was higher Na concentration in the early part of the growing season compared to late season. However Year 1 was higher for Na in the middle growing period (July and August). Biomass S and Cu concentrations were higher in the early growing season compared to the late growing season in each year. The biomass Fe percent was higher in early growing period compared to late growing period. However, Year 3 had nonsignificant differences of Fe percent among growing months. Biomass Zn concentration remained constant throughout the growing season. Biomass Mg concentration in growing season was constant for Years 1 and 3, while Year 2 had higher Mg in the early growing period. Biomass total C increased over the growing season in each year, indicating the increasing trend of photosynthetic accumulation in the biomass. Biomass ash concentration remained constant for Years 2 and 3. However, Year 1 biomass ash percent was higher in the early growing period compared to the later growing period. One possible reason might be the low biomass accumulation in the Year 1 early growing period compared to Years 2 and 3. The rainfall for May and June of 2007 (for study Year 1) was excessively higher and solar radiation was lower compared to the 30-yr normal as well as study Years 2 and 3 (Tables 2 and 3). Acid detergent fiber, NDF, and ADL concentrations increased during the growing months in 3-yr study.

Soil Properties

In general, most soil properties remained unchanged throughout the winter (Tables 7 and 8). Soil pH was constant for both winter and growing seasons. In winter, NO_3–N, P, K, Fe, Zn, and Cu concentrations were constant. Soil SO_4 was constant in the winters of the Years 1 and 2 but was different for the Year 3. The EW was higher in SO_4 compared to LW. Calcium and Mg were constant in winters of Years 2 and 3. Although Ca and Mg were different among winter months in Year 1, there were no significant contrast differences between EW and LW. Significant differences among winter months were observed for B in Years 1 and 3 but not in Year 2. The contrast between EW vs. LW for B

Table 8. Soil pH, organic matter (OM), and soil chemicals in switchgrass field for different months.

		Month												
Variable	**Year**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**LSD**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**LSD**
pH	1	6.1	6.1	6.1	6.0	6.0	0.2	6.0	6.1	6.0	6.0	6.0	6.0	0.1
	2	6.2	6.2	6.2	6.1	6.2	0.2	6.3	6.2	6.3	6.3	6.2	6.2	0.2
	3	6.2	6.1	6.1	6.0	6.1	0.2	6.1	6.0	6.1	6.0	6.1	6.0	0.1
NO_3–N, mg kg^{-1}	1	0.91	0.75	0.66	0.66	0.66	0.36	0.58	1.00	0.58	0.50	1.16	1.33	0.35
	2	0.91	1.08	1.16	0.75	1.00	0.80	0.83	0.58	0.75	0.58	1.16	1.08	0.34
	3	0.66	0.66	0.50	0.58	0.75	0.32	0.50	0.50	0.58	1.25	1.16	1.16	0.21
P, mg kg^{-1}	1	30	31	29	32	30	4	31	31	30	30	31	30	3
	2	28	27	24	27	25	5	27	26	26	24	25	24	2
	3	23	25	22	24	25	4	26	26	26	23	23	22	14
K, mg kg^{-1}	1	112	126	112	122	114	14	122	152	135	143	152	140	23
	2	122	121	109	116	109	19	123	111	131	129	131	122	9
	3	107	124	124	114	112	14	117	124	133	130	138	121	9
SO_4, mg kg^{-1}	1	13	13	12	13	12	1	12	12	11	10	12	11	1
	2	11	11	10	10	9	2	9	9	9	10	9	8	1
	3	9	10	10	9	8	1	8	9	8	9	9	9	1
Ca, mg kg^{-1}	1	1461	1651	1503	1569	1409	154	1521	1670	1552	1648	1629	1510	198
	2	1293	1469	1365	1416	1307	176	1414	1402	1422	1339	1394	1397	93
	3	1371	1462	1288	1409	1318	183	1475	1395	1480	1432	1441	1364	95
Mg, mg kg^{-1}	1	290	332	295	307	286	32	311	346	328	336	332	323	34
	2	278	311	277	289	270	33	297	282	298	282	288	279	17
	3	264	300	268	272	268	28	297	290	301	291	286	271	15
Fe, mg kg^{-1}	1	55	48	50	57	51	16	62	69	63	67	76	70	11
	2	49	53	47	57	48	10	68	60	61	55	66	64	8
	3	53	59	52	59	56	13	61	71	70	70	70	64	7
Zn, mg kg^{-1}	1	1.10	1.03	1.02	1.23	1.05	0.26	1.17	1.28	1.18	1.05	1.15	0.90	0.16
	2	1.07	1.10	1.01	1.06	1.02	0.21	1.22	1.06	1.01	1.04	1.04	0.91	0.13
	3	0.93	1.13	0.94	0.98	0.87	0.18	1.07	1.10	1.25	0.92	1.04	0.83	0.18
B, mg kg^{-1}	1	0.39	0.38	0.34	0.39	0.32	0.05	0.35	0.41	0.34	0.37	0.39	0.34	0.07
	2	0.29	0.32	0.30	0.29	0.31	0.07	0.32	0.28	0.29	0.31	0.31	0.32	0.03
	3	0.23	0.28	0.27	0.23	0.22	0.10	0.21	0.20	0.23	0.22	0.20	0.19	0.03
Cu, mg kg^{-1}	1	1.28	1.33	1.37	1.50	1.40	0.30	1.42	1.53	1.40	1.45	1.42	1.35	0.21
	2	1.38	1.61	1.42	1.64	1.49	0.21	1.69	1.50	1.59	1.48	1.62	1.62	0.14
	3	1.54	1.75	1.44	1.61	1.47	0.25	1.55	1.52	1.55	1.60	1.61	1.41	0.10
OM, %	1	1.42	1.65	1.45	1.60	1.44	0.17	1.82	1.89	1.85	1.68	2.02	1.67	0.29
	2	1.00	1.28	0.92	1.02	0.76	0.32	0.99	1.06	1.05	1.00	1.08	1.05	0.20
	3	1.68	1.99	1.77	1.85	1.69	0.22	1.93	1.77	2.17	2.00	2.03	1.86	0.26

concentration was not significant for Year 1, but was significant for the Year 3 (Tables 7 and 8). The OM concentration was significantly different ($P < 0.05$) among the winter months for Years 1 and 2 but not for Year 3. The contrast between EW and LW was not significant for Years 1 and 2. Therefore, the differences in OM concentrations might be due to sampling variability

During the growing seasons, the month effect was significant for most of the soil nutrients, but nonsignificant for Ca, B, and OM contents. Soil NO_3–N was higher in the late growing period (August, September, and October) compared to the early growing period (May, June, and July). Soil P was different among the growing season months for Years 2 and 3, but not in Year 1. The early growing season soil P concentration was higher compared to the late growing season in Years 2 and 3. Soil K was significantly different among growing season months for Year 2 but not in Years 1 and 3. Soil K was higher in the early growing season compared to the late growing season in Year 2. Although soil SO_4 varied among growing months for each of the three growing seasons, contrasts between early and later growing season were not significant for Years 1 and 2, but Year 3 showed lower SO_4 concentration in the early growing season. Soil Mg concentration was constant for Years 1 and 2, but was lower in the late growing period of Year 3. The Year 1 growing season soil Fe concentration was not significantly different among months, and soil Fe concentration was not different between the early and late growing seasons in Years 2 and 3. Although soil Cu concentration varied among growing months during Years 2 and 3, the contrast between the early and late growing season months was not significant (Tables 7 and 8).

Previous experiments reported that switchgrass grown for bioenergy feedstock production is best harvested one time after senescence (Parrish et al., 2008). The advantages of the one-cut system include maximum long-term biomass yields and persistence of switchgrass stands. However, it would be a challenge to harvest massive hectarages of switchgrass soon after senescence. Our study reported that switchgrass biomass yield did not decline significantly during early winter months over 3 yr. In this study, the main effect of year and the year × month interaction significantly affected winter biomass yields. Biomass yield reduction mainly occurred in February through March, suggesting that extending harvest from October (when switchgrass plants normally become dormant) to the early winter months (November through January) may not substantially lose harvestable biomass. Biomass nutrient concentrations in winter months were quite stable with the exception of P, K, and S. The concentrations of P, K, and S in biomass, although small, declined significantly over winter months and would result in better feedstock for certain conversion technologies such as gasification. Most soil nutrients and pH did not change much across winter harvests, suggesting limited effects of winter biomass harvest timing on soil properties.

CONCLUSIONS

Harvest management is an important component of the switchgrass biomass production chain as it is related to biomass yield and quality, harvest equipment logistics, and feedstock storage. Our study demonstrates that aboveground biomass yield of standing field-cured switchgrass did not decline much in early winter months, but decreased significantly in late winter months before spring regrowth. These results suggest that it may be beneficial if a one-cut harvest time window is extended to the early winter months, consequently harvest machinery cost would be substantially reduced and substantial storage space would be saved as compared to the harvest management otherwise. In addition, harvest during winter months could be beneficial to the conversion technologies, which do not need or have problems with P, K, and S in the biomass; these elements decrease as winter progresses, while other quality components remain relatively stable. Winter harvest of switchgrass does not affect negatively on soil property for the subsequent crop growing. Therefore, these findings will be valuable in the harvest management of switchgrass biomass production.

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