Switchgrass Biomass Production in the Midwest USA: Harvest and Nitrogen Management

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ABSTRACT

Information on optimal harvest periods and N fertilization rates for switchgrass (*Panicum virgatum* L.) grown as a biomass or bioenergy crop in the Midwest USA is limited. Our objectives were to determine optimum harvest periods and N rates for biomass production in the region. Established stands of 'Cave-in-Rock' switchgrass at Ames, IA, and Mead, NE, were fertilized 0, 60, 120, 180, 240, or 300 kg N ha^{-1}. Harvest treatments were two- or one-cut treatments per year, with initial harvest starting in late June or early July (Harvest 1) and continuing at approximately 7-d intervals until the latter part of August (Harvest 7). A final eighth harvest was completed after a killing frost. Regrowth was harvested on previously harvested plots at that time. Soil samples were taken before fertilizer was applied in the spring of 1994 and again in the spring of 1996. Averaged over years, optimum biomass yields were obtained when switchgrass was harvested at the maturity stages R3 to R5 (panicle fully emerged from boot to postanthesis) and fertilized with 120 kg N ha^{-1}. Biomass yields with these treatments averaged 10.5 to 11.2 Mg ha^{-1} at Mead and 11.6 to 12.6 Mg ha^{-1} at Ames. At this fertility level, the amount of N removed was approximately the same as the amount applied. At rates above this level, soil NO_3–N concentrations increased.

Switchgrass is a perennial warm-season C_4 photosynthetic system grass that is native to the tallgrass prairie regions of North America (Moser and Vogel, 1995). Based on a series of evaluation trials, the U.S. Department of Energy has identified switchgrass as the most promising species for development into an herbaceous biomass fuel crop (Vogel, 1996). It has an array of desirable attributes for use as a bioenergy crop, including broad adaptation and high yields on marginal and erosive croplands, and it can be harvested with conventional hay-making equipment. Major costs associated with producing switchgrass biomass include N fertilization, harvesting, and transportation (Keeney and DeLuca, 1992). The number of harvests and the yields per harvest affect the economics of harvesting switchgrass biomass.

Research has been conducted on fertilizer requirements of native warm-season grasses, including switchgrass when managed for hay or grazing. The results of these trials have recently been reviewed and summarized by Brejda (2000). In brief, the main fertilizer requirement of switchgrass is N. Switchgrass usually grows in association with mycorrhizae and is a very efficient user of many soil nutrients, including P (Brejda et al., 1998; Brejda, 2000; Muir et al., 2001). The N requirement of switchgrass used for hay or grazing largely depends on the yield potential of the site, productivity of the switchgrass cultivar, and management practices being used. In the central Great Plains and Midwest states, optimum N rates for switchgrass managed for pasture or hay range from about 50 to 120 kg ha^{-1} (Brejda, 2000). In Texas, the optimum N fertilization rate for 'Alamo' switchgrass managed for biomass production was 168 kg ha^{-1} (Muir et al., 2001).

Limited research information is available on harvest schedules for switchgrass managed as a bioenergy crop. In a previous study in Iowa, the greatest total switchgrass yields were achieved when the first harvest was taken at the stem elongation stage when the fourth and fifth nodes were palpable and when the regrowth was harvested 6 wk later (George and Obermann, 1989). In Georgia, greater yields were achieved when plants were harvested once during the growing season when they reached either 61 or 91 cm in height and the regrowth harvested in the fall after a killing frost compared with a single harvest in the fall after a killing frost (Beaty and Powell, 1976). In Tennessee, Reynolds et al. (2000) evaluated two harvest treatments (early summer and late autumn vs. late autumn) for switchgrass grown at a constant N fertilization rate of 50 kg ha^{-1} yr^{-1} for 5 yr. Treatments with the highest biomass yields varied with years. Total N concentration of switchgrass herbage was significantly lower in biomass in late autumn compared with summer harvests.

Information on the interaction of N rates and harvest regimes is not available for managing switchgrass for biomass production in the Midwest. The main objectives of this research were to determine optimum harvest periods and N fertilization rates for the production of switchgrass as a biomass crop in the Midwest. The treatments resulted in plots that differed significantly in soil NO_3 concentrations, which provided us an opportunity to determine the response of switchgrass biomass yields to residual NO_3 concentrations in the year following completion of the main study. Utility of soil tests depend on significant response of the crop to soil nutrient concentrations.

MATERIALS AND METHODS

Experiment Design and Establishment

This research was conducted at the University of Nebraska Agricultural Research and Development Center near Mead,

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Abbreviations: NIRS, near-infrared reflectance spectrometer.

Table 1. Growing season rainfall for 1994 through 1996 at Ames, IA, and Mead, NE.

	Ames				Mead			
Month	1994	1995	1996	30-yr avg.	1994	1995	1996	30-yr avg.
	mm							
Apr.	70	131	33	86	32	109	82	71
May	44	110	194	108	36	145	185	114
June	142	88	132	133	230	33	140	104
July	58	101	104	95	107	26	37	83
Aug.	113	78	124	100	43	34	76	104
Sept.	114	68	81	88	95	63	51	86
Growing season total	541	576	668	610	543	410	571	561

NE, and at the Iowa State University Agronomy and Agricultural Engineering Research Center at Ames, IA. The soil at the Ames site was a Webster–Nicollet complex (fine-loamy, mixed, mesic Typic Haplaquoll-Aquic Hapludoll). Soil at the Mead site was a Sharpsburg silty clay loam (fine smectitic mesic typic Argiudoll). Precipitation amounts received during the growing season were recorded on-site at both locations each year (Table 1).

The experimental design at both sites was a randomized complete block with a split-plot arrangement of treatments; main plots were N treatments and subplots were harvest treatments. Each field was blocked before planting into four ranges or blocks that were separated by 1.5-m-wide alleys. Each block contained 50 plots that were 1.5 m wide by 6.1 m long. The two outside plots were treated as border plots. The interior 48 plots of a block were subdivided into six sets of eight plots. Each set of eight plots was treated as a main plot and randomly assigned a specific fertility treatment. Each of the eight plots within a main plot was designated a subplot and randomly assigned to a specific harvest treatment.

The plots and alleys were planted to Cave-in-Rock switchgrass at a rate of 430 pure live seed m^{-2} using a small-plot drill (Vogel, 1978). The Mead and Ames sites were seeded on 24 and 26 May 1993, respectively, into a clean, firmly packed seedbed. After planting, each site was treated with 2.24 kg a.i. ha^{-1} atrazine (2-chloro-4-ethylamino-6-isoproplyamino-*s*-triazine) to help control weeds. Satisfactory stands were obtained. After a killing frost in the autumn of 1993, all biomass above a 10-cm cutting height that had accumulated during the establishment year was removed. Four adjacent blocks at each site were used for this study.

In 1994, soil samples were collected from the 0- to 30-, 30- to 60-, 60- to 90-, and 90- to 120-cm depths from all main plots of the four replicates during the week of 18 April at Mead and on 4 and 5 May at Ames. In 1996, soil samples were again collected on 6 May from all subplots at Mead and on 4 June from subplots of Blocks 2 and 3 at Ames. The soil samples were analyzed for NO_3–N concentrations using the Cd reduction method (Keeney and Nelson, 1982) by the Soil and Plant Analytical Laboratory of the Department of Agronomy and Horticulture, University of Nebraska.

The switchgrass stand at Mead was treated with 2.24 and 2.24 kg a.i. ha^{-1} atrazine and metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl acetamide], respectively, on 16 May 1994 and 2.24, 2.24, and 1.1 kg a.i. ha^{-1} atrazine, metolachlor, and 2,4-D (2,4-dichlorophenoxyacetic acetic acid), respectively, on 31 May 1995 for weed control and to maintain pure stands of switchgrass. The switchgrass stand at Ames was treated with 2.24, 2.24, and 1.12 kg a.i. ha^{-1} atrazine, metolachlor, and 2,4-D, respectively, on 20 May 1994. In 1995, the Ames experiment was treated with 1.1 kg a.i. ha^{-1} 2,4-D in the spring for weed control.

Nitrogen and Harvest Treatments

Nitrogen treatments were 0, 60, 120, 180, 240, or 300 kg N ha^{-1}, and the N source was ammonium nitrate (NH_4NO_3). The ammonium nitrate was preweighed and hand-broadcast on each individual subplot of a main-plot N treatment. In 1994, the N treatments were applied on 26 May at Ames and on 10 June at Mead. In 1995, the N treatments were applied on 24 May at Mead and 25 May at Ames.

Harvest treatments were eight different harvest dates starting in late June or early July and continuing at approximately 7-d intervals until mid-August when the 7th harvest was completed. The final harvest was completed after a killing frost in mid-October. Regrowth was harvested on previously harvested plots (Harvests 1 to Harvest 7) at the time of the eighth harvest. Depending on year and location, Harvest 1 occurred at the late stem elongation stages or boot stage, and the final summer harvests were at postanthesis or early seed development stages (Table 2). Harvests were scheduled so that all summer harvests were completed before 1 Sept. because stand loss can occur in switchgrass if there are fewer than 6 wk between the last harvest and a killing frost (Moser and Vogel, 1995). Before each harvest, the developmental stage of the switchgrass stands was visually scored using the index system of Moore et al. (1991).

The alleys were harvested and biomass removed at the time of the first harvest and then periodically trimmed at subsequent harvests. Biomass yield was determined by cutting and weighing a 0.91-m-wide swath the length of each subplot using a flail-type plot harvester with a cutting height of 10

Table 2. Initial harvest date, switchgrass growth stage at each date, and numerical index scores for each growth stage for eight harvest treatments in 1994 and 1995 at Ames, IA, and Mead, ND.

	Ames		Mead	
Harvest treatment	Harvest date	Index score†	Harvest date	Index score†
	1994			
1	28 June	3.0	15 July	3.1
2	12 July	3.3	22 July	3.3
3	21 July	3.3	29 July	3.5
4	27 July	3.5	5 Aug.	3.7
5	4 Aug.	3.5	11 Aug.	3.7
6	17 Aug.	3.7	18 Aug.	3.9
7	25 Aug.	3.9	29 Aug.	4.0
8	1 Nov.	‡	27 Oct.	‡
	1995			
1	29 June	2.5	30 June	2.5
2	12 July	3.0	7 July	2.6
3	19 July	3.1	13 July	3.1
4	26 July	3.1	18 July	3.1
5	2 Aug.	3.5	25 July	3.3
6	9 Aug.	3.5	4 Aug.	3.5
7	21 Aug.	3.9	17 Aug.	3.7
8	17 Nov.	‡	8 Nov.	‡

† Index scores from Moore et al. (1991). 2.5, stem elongation (fifth node palpable); 2.6, stem elongation (sixth node palpable); 3.0, boot stage; 3.1, inflorescence emergence; 3.3, spikelet fully emerged; 3.5, peduncle fully elongated; 3.7, anther emergence and/or anthesis; 3.9, post anthesis and/or fertilization; and 4.0, caryopsis visible.
‡ Plants harvested after a killing frost for which Moore et al. (1991) did not have a designated growth stage.

cm. The outer edges of the subplots were not harvested for yield to reduce border effects. After yields were determined for a specific harvest treatment, the biomass from the borders of the harvested subplots was removed but not weighed. Harvested material was weighed fresh in the field. Before each harvest, subsamples were hand-collected from each harvested subplot, weighed, dried at 50°C for 72 h in a forced-air oven, and reweighed to determine dry matter content.

In 1996, no fertilizer or other treatments were applied to any plots or subplots. A single biomass harvest was taken at the seed development stage on 13 August at Mead and 28 August at Ames. It was believed that the previous fertility and harvest treatments had likely produced subplots that differed substantially in residual soil N levels, which would be detected by the soil tests made in the spring of 1996. The objective of the 1996 biomass harvest was to evaluate the biomass yield response of switchgrass to the residual N levels.

The samples used to determine dry matter content were also used to determine N concentration of the biomass. After drying, the samples were ground in a Wiley shear mill (Thomas Scientific, Swedesboro, NJ) to pass a 1-mm screen and reground to uniformity in a Udy cyclone impact mill with a 1-mm screen (Udy Corp., Fort Collins, CO). These subsamples were analyzed for total N using a near-infrared reflectance spectrometer (NIRS; Technicon Infralyzer 500, Bran and Luebbe Analyzing Technologies, Buffalo Grove, IL) across a wavelength range of 1100 to 2500 nm with 2-nm steps. A subset of the samples were analyzed by the Kjeldahl procedure (Keeney and Nelson, 1982) for developing and verifying NIRS prediction equations. The NIRS calibration statistics for N concentration of the biomass are as follows: N = 215, mean = 1.13, standard error of calibration = 0.04, R^2 = 0.99, and standard error of prediction = 0.06. Nitrogen removal by the biomass harvests was determined by multipling biomass N concentration by biomass yield.

Statistical Analysis

The 1994 and 1995 data were initially analyzed across locations and years. The location × N rate × harvest treatment × year interaction was significant for most response variables. Therefore, the data were analyzed separately for each location using a split split-plot design with N rates as the whole plot, harvest treatments as the subplot, and years as the sub-subplot. Years were treated as repeated measures in the analysis, and appropriate *F*-tests followed Steel and Torrie (1980, p. 396–397). The N rate treatments were partitioned into linear and quadratic components using orthogonal polynomials (Steel and Torrie, 1980).

The 1996 biomass yields were regressed on mean soil NO_3–N concentrations of the entire 120-cm profile using the GLM procedure in SAS (SAS Inst., 1990) to determine the response of switchgrass biomass yield to spring soil NO_3–N concentrations. The relationship between biomass yield and soil NO_3–N was evaluated separately for Ames and Mead.

RESULTS AND DISCUSSION

Biomass Yields

Satisfactory stands were maintained for the duration of the study as based on annual visual appraisals. As expected, harvest treatment and N rate had significant effects on switchgrass biomass yields at both locations (Table 3). Year effects also were significant but were lower in magnitude. Year effects were likely due to differences in growing season rainfall (Table 1). At Ames, 1994 was a drier year than 1995, but the opposite occurred at Mead. Harvest × year effects were significant for all yield variables except regrowth yield at Mead, but relative to harvest and N main effects, they were very minor sources of variation and were probably due to differences in time of harvest between years due to weather-related conditions. Harvest treatment × N rate interactions were not significant, indicating the response to each main treatment effect can be evaluated independently (Table 3).

Harvest Treatments

The responses of switchgrass biomass yield to the different harvest treatments were similar at both locations (Fig. 1). First-harvest switchgrass biomass yields increased with increase in physiological maturity (Fig. 1). Peak yields occurred at Harvests 6 and 7. These harvests occurred after all plants were at the maturity index score 3.3 (all spikelets visible and panicle fully emerged from the boot) or higher. In contrast, with regrowth, the earlier the first harvest was, the greater the regrowth yields. Regrowth yields had a smaller contribution to total yield than first-cut yields. At both locations, the harvests after a killing frost had signifi-

Table 3. Analysis of variance and mean squares for switchgrass biomass yields in response to six N rates and eight harvest treatments during the growing season in 1994 and 1995 at Ames, IA, and Mead, NE.

		First harvest		Regrowth harvest		Total yields	
Source of variation	df	Ames	Mead	Ames	Mead	Ames	Mead
Block	3	17.7**	13.1	3.2**	2.1	26.1**	19.3
N rate	5	201.3**	36.1**	10.1**	0.5	294.7**	42.1
N linear	(1)	(844.7)**	(121.6)**	(47.0)**	(2.0)	(1290.0)**	(155.0)**
N quadratic	(1)	(146.1)**	(3.2)	(0.9)	(<0.1)	(170.3)**	(3.3)
Error a	15	3.0	4.4	0.6	0.9	2.2	6.9
Harvest	7	400.8**	220.9**	40.7**	26.6**	276.8**	137.7**
N rate × harvest	35	5.1	4.0	1.0	0.5	6.8	4.8
Error b	126	3.6	3.3	0.7	0.5	4.7	4.1
Year	1	60.7**	87.2**	3.2*	8.2*	36.0	41.9*
Error c	3	5.7	2.8	0.3	0.9	7.2	2.2
N Rate × year	5	4.9	1.4	0.3	0.6	4.9	1.4
N linear by year	(1)	(9.7)	(<0.1)	(<0.1)	(1.4)	(10.2)	(1.6)
N quadratic by year	(1)	(4.1)	(2.0)	(0.3)	(0.3)	(2.1)	(4.1)
Error d	15	2.3	4.9	0.3	0.4	2.7	4.4
Harvest × year	7	21.1**	38.1**	1.4**	0.5	21.3**	33.0**
N × Harvest × year	35	2.6	6.0**	0.5	0.6	3.4	6.5**
Residual	126	2.2	2.4	0.4	0.4	2.8	3.1

* Significant at the 0.05 level.
** Significant at the 0.01 level.

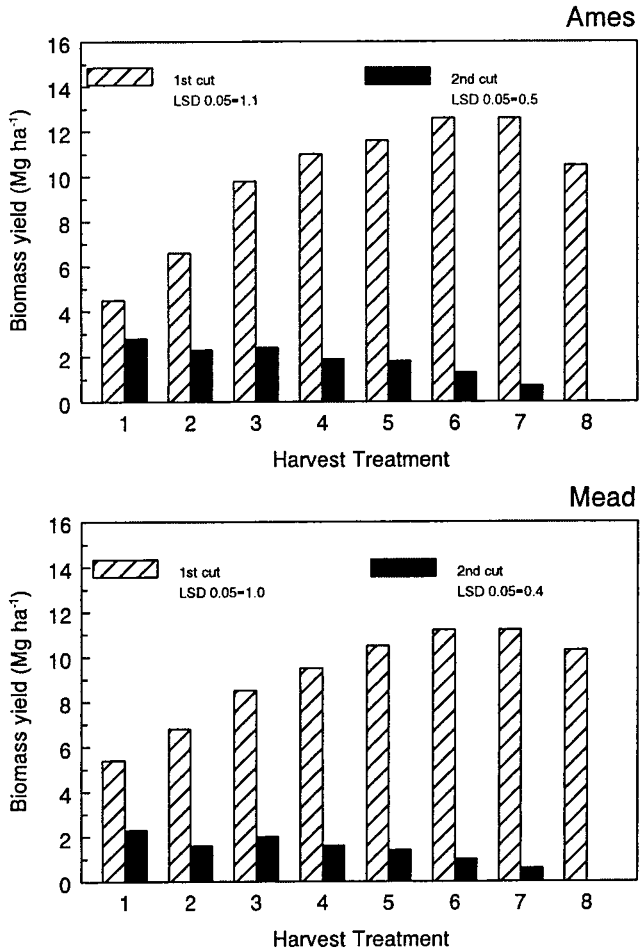

Fig. 1. Biomass yields of first harvest or cut and regrowth harvest for eight harvest treatments at Ames, IA, and Mead, NE, averaged over 1994 and 1995 and over N rates. Harvest treatments are two- or one-cut harvests based on initial harvest dates starting in late June or early July (Harvest 1) and continuing at approximately weekly intervals until the latter part of August (Harvest 7). A final eighth harvest was completed after a killing frost, at which time regrowth was also harvested on previously harvested plots for Harvest Treatments 1 through 7.

cantly lower yields than harvests made after peduncles were fully elongated (Harvests 6 and 7).

Switchgrass is photoperiod sensitive (Moser and Vogel, 1995), and its morphological development is largely determined by its response to photoperiod (Mitchell and Moser, 2000). Mitchell et al. (1997) used information from four Midwest environments to demonstrate that the morphological development of switchgrass could be predicted by linear regression ($R^2 = 0.96$) on day of the year. Hence, the optimal time of harvest for maximum biomass yield of switchgrass cultivars that are in the same maturity group as Cave-in-Rock for sites with similar latitudes in the Midwest as Ames, IA, and Mead, NE, would be during the first 3 wk of August when the plants would be at 3.3 (=R3) to 3.5 (=R5) stages of development (Moore et al., 1991) (Table 1 and Fig. 1).

Nitrogen Fertilization

Switchgrass first-harvest and total biomass yields responded linearly at Mead and curvilinear at Ames to

Table 4. Soil NO_3–N concentrations at four depths under switchgrass stands before the start of the study in 1994 and in spring 1996 after treatment with six N rates in 1994 and 1995 at Ames, IA, and Mead, NE, averaged across harvest treatments.

		1996					
		N rates (kg ha^{-1}) applied in 1994 and 1995					
Depth (cm)	1994	0	60	120	180	240	300
	mg kg^{-1} NO_3–N						
			Ames				
0–30	4.6	1.1	0.8	1.1	0.8	1.1	0.9
30–60	2.0	1.0	0.7	0.9	1.0	1.4	1.8
60–90	1.6	1.0	0.7	0.9	1.8	3.1	3.0
90–120	1.6	1.0	0.8	0.8	1.4	2.8	4.5
SE	0.1			0.5†			
			Mead				
0–30	4.0	1.5	2.1	2.9	4.4	7.3	13.9
30–60	4.5	1.0	1.4	2.7	6.0	7.8	16.6
60–90	6.2	1.0	1.1	1.2	1.4	1.8	5.8
90–120	6.9	0.8	1.1	1.1	1.2	2.0	3.8
SE	0.4			2.9†			

† Standard error value applies to all values for 1996.

increased applications of N fertilizer (Table 3 and Fig. 2). At Mead, the differences in first-harvest biomass yields among N rates ≥60 kg ha^{-1} were ≤0.6 Mg ha^{-1} (Fig. 2). At Ames, first-harvest biomass yields for N treatment rates of 180 to 300 kg ha^{-1} did not differ. The different responses to fertility treatments between Ames and Mead was probably due to the higher yields obtained at Ames due to greater precipitation received at that site (Table 1) and greater initial soil NO_3–N concentration at Mead (Table 4). Because of higher initial soil NO_3–N at Mead, yields at the zero N rate were higher at Mead, and the response to increasing N rates was lower at Mead than at Ames (Fig. 2). Comparisons of soil NO_3–N concentrations for soil samples collected at Mead and Ames in 1994 before the fertilization treatments and in 1996 before the start of the growing season indicate that switchgrass had reduced soil NO_3–N concentration with the 0 and 60 kg ha^{-1} N rates at Mead and also at Ames, but to a lesser extent (Table 4). Regrowth yields at Ames increased linearly with increasing rates of N, but at Mead, the N treatment had no significant effect on regrowth yields (Table 3 and Fig. 2).

Nitrogen Removal

Nitrogen removal by switchgrass biomass harvest was significantly affected by both harvest treatment and N fertilizer rate (Table 5). The N rate × harvest treatment interaction was significant for the first harvest at Mead and for total yields at Ames and Mead, but the mean squares were very small compared with the mean squares of the N and harvest main effects. Other interaction effects were significant but also were small according to the relative magnitude of their mean squares. The large mean square for years at Mead was probably due to the reduction in soil NO_3–N following the first harvest year and its subsequent effect on yield. Hence, the effect of N fertilizer rate and harvest treatment on N removal by switchgrass biomass harvest can be considered independently.

First-harvest N removal at Ames increased until Har-

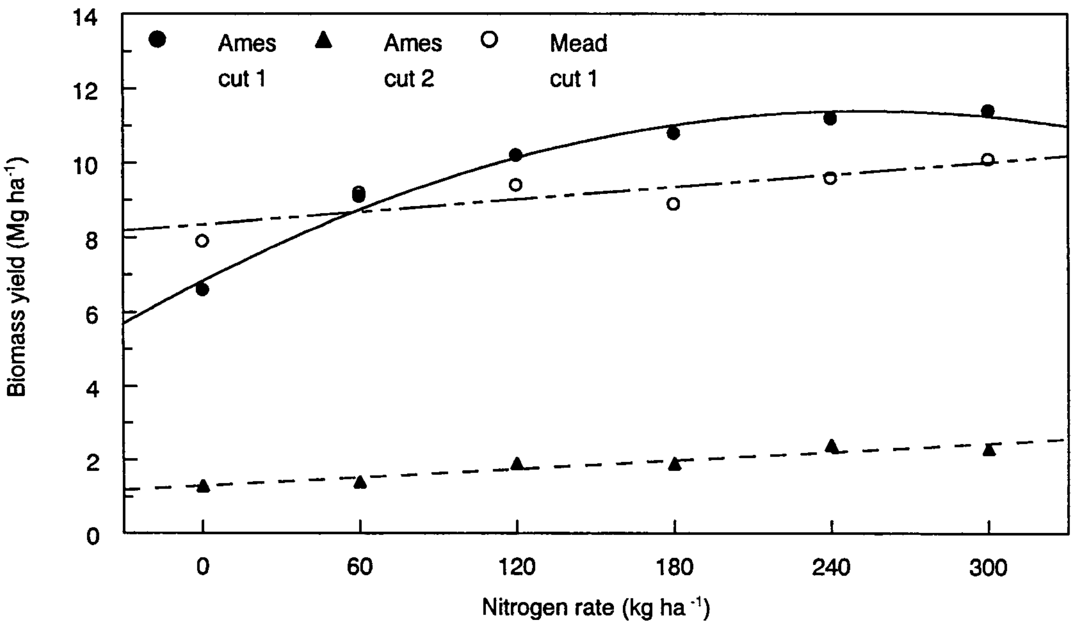

Fig. 2. Biomass yields of first harvest or cut and regrowth harvest with increasing rates of N at Ames, IA, and Mead, NE, averaged over harvest treatments for 1994 and 1995. Regression equations were Ames cut 1, $Y = 6.9 + 0.036X - 0.00007X^2$, $r^2 = 0.98$, root mean square error (RMSE) = 0.3; Ames cut 2, $Y = 1.29 + 0.0039X$, $r^2 = 0.90$, RMSE = 0.2; and Mead cut 1, $Y = 8.38 + 0.0055X$, $r^2 = 0.70$, RMSE = 0.5.

vest 4 and decreased with later harvests (Fig. 3). At Mead, first-harvest N removal increased until Harvest 5 and then decreased with later harvests (Fig. 3). At both locations, N removal with Harvest 8 (after a killing frost) was >50% lower than for any other harvest treatment.

Biomass N removal is a function of biomass yield and N concentration of the biomass. Biomass N concentration increased with increasing N fertilization rates (Fig. 4). Biomass N concentration for the first-harvest treatments increased curvilinearly while N concentration of the second harvests increased in a linear manner. As discussed previously, biomass yields increased with increased maturity or initial harvest date. First-harvest biomass N concentration probably was diluted by an increase in cell wall concentration of the forage as it matured, resulting in the curvilinear response to increased N fertilization rates. At Harvest 1 at Ames and Mead, average biomass N concentrations were 17.7 and 18.5 g kg^{-1}, respectively, but by Harvest 7, N concentration had decreased to 8.3 and 9.7 g kg^{-1}, respectively. Reynolds et al. (2000) also reported a decrease in N concentration of switchgrass biomass as plants became senescent. Biomass N concentration for Harvest 8 was about 5 g kg^{-1} for both locations. The significantly smaller amount of N removed by Harvest 8 was due to both reduced yields and reduced N concentration. There were significant differences among harvest treatments for the regrowth harvest N removed in the biomass, but these differences were small relative to first-harvest N removal (Fig. 3).

McKendrick et al. (1975) reported significant decreases in tiller N concentrations corresponding with significant increases in rhizome N concentrations in late

Table 5. Analysis of variance and mean squares for N removal by switchgrass in response to six N rates and eight harvest treatments during the growing season in 1994 and 1995 at Ames, IA, and Mead, NE.

		First harvest		Regrowth harvest		Total yields	
Source of variation	**df**	**Ames**	**Mead**	**Ames**	**Mead**	**Ames**	**Mead**
Block	3	2 398*	7 567**	441**	327*	4 565**	10 172**
N rate	5	99 627**	31 764**	2 885**	232	129 230**	36 873**
N linear	(1)	(462 718)**	(152 746)**	(14 161)**	(1 127)**	(626 545)**	(178 282)**
N quadratic	(1)	(20 079)**	(1 658)	(18)	(<1)	(18 961)**	(1 652)
Error a	15	469	551	49	95	601	904
Harvest	7	29 024**	30 449**	452**	825**	43 800**	46 052**
N rate × harvest	35	1 219	970*	44	50	1 637**	1 093*
Error b	126	382	558	34	51	445	629
Year	1	3 504**	138 772**	143*	687	4 951	157 635**
Error c	3	683	211	76	136	495	505
N Rate × year	5	943	702	11	153*	1 080	851
N linear by year	(1)	(3 733)	(146)	(20)	(384)*	(4 257)*	(924)
N quadratic by year	(1)	(32)	(1 584)	(21)	(85)	(99)	(2 346)
Error d	15	453	534	17	46	520	422
Harvest × year	7	2 566**	4 651**	241**	120	2 637**	4 519**
N × harvest × year	35	476*	1 192**	32**	61	568*	1 148**
Residual	126	273	560	13	34	293	637

*** Significant at the 0.05 level.**
**** Significant at the 0.01 level.**

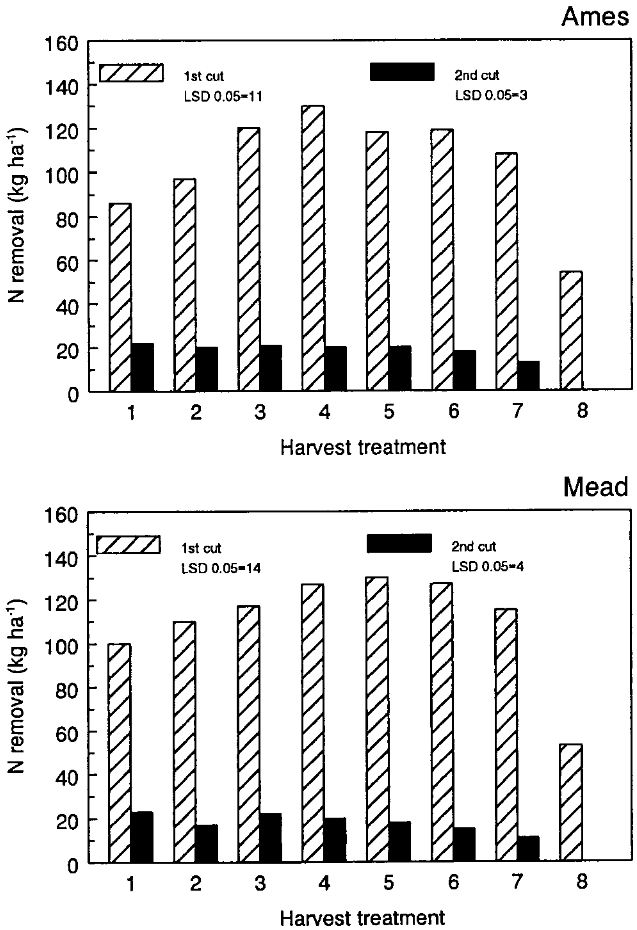

Fig. 3. Nitrogen removal in first and regrowth biomass harvest or cuts for switchgrass biomass harvest treatments at Ames, IA, and Mead, NE, averaged across N treatments for 1994 and 1995.

July and early August in big bluestem (*Andropogon gerardii* Vitman) and indiangrass [*Sorghastrum nutans* (L.) Nash], two native warm-season grasses that are ecologically and physiologically similar to switchgrass. Similarly, Clark (1977) reported that as much as one-third of the N in blue grama [*Bouteloua gracilis* (H.B.K.) Lag. Ex Steud.] tillers was translocated to belowground organs during the latter part of the growing season. With the switchgrass stands at the two sites in our experiment, appreciable amounts of N may have been translocated to belowground organs between Harvest 7, which was taken at or near anthesis, and Harvest 8, which was taken after a killing frost. If significant levels of N are translocated to stem bases and roots, the translocated N could be used in the production of new growth the following spring and could significantly reduce N input requirements in switchgrass stands harvested for biomass after a killing frost.

Nitrogen removal increased significantly with increased N rate for both first, second, and total biomass yields (Table 5 and Fig. 5). The response was curvilinear for first harvest at Ames but was linear for first harvest at Mead and regrowth harvest at both locations. Maximum total N removal by both harvests was 176 kg ha^{-1} at Mead in 1994 and 173 kg ha^{-1} at Ames in 1995. Because the maximum N removal at both sites was approximately 170 kg ha^{-1}, N fertilization applied at rates above the level of removal may result in a buildup of N in the soil, as indicated by soil NO_3–N concentrations in Table 4.

Soil Nitrate-Nitrogen Concentrations

In 1996, after conducting the study for two consecutive years, there were differences among plots for soil NO_3–N concentrations (Table 4). Analysis of variance

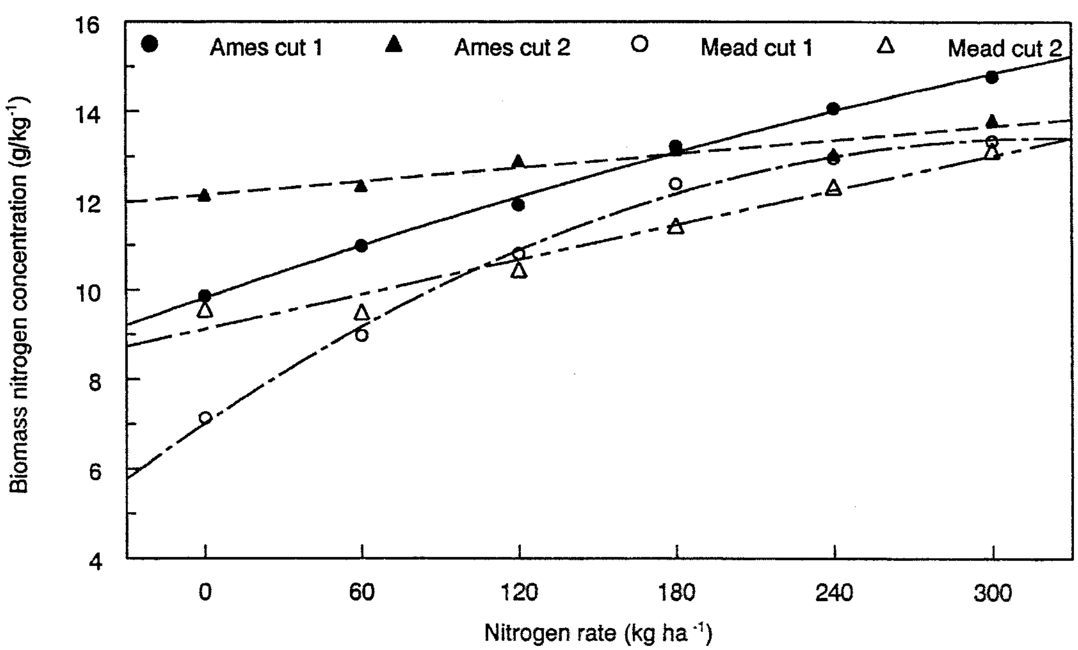

Fig. 4. Biomass N concentration of first harvest and regrowth harvest or cut with increasing rate of N fertilization at Ames, IA, and Mead, NE, in 1994 and 1995. Regression equations were Ames cut 1, $Y = 9.6 + 0.023X - 0.000019X^2$, $r^2 = 0.99$, RMSE = 0.2; Ames cut 2, $Y = 12.1 + 0.006X$, $r^2 = 0.91$, RMSE = 0.2; Mead cut 1, $Y = 7 + 0.04X$, $r^2 = 0.99$, RMSE = 0.2; and Mead cut 2, $Y = 9.1 + 0.013X$, $r^2 = 0.96$, RMSE = 0.3.

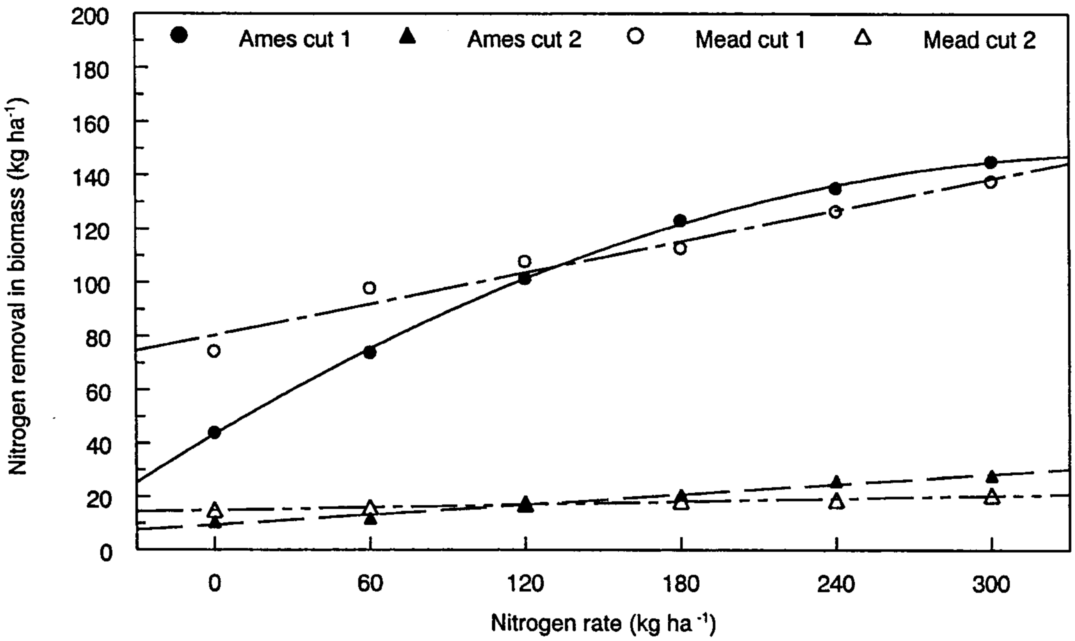

Fig. 5. Nitrogen removal in first and regrowth biomass harvests or cuts from switchgrass plots treated with increasing rates of N rates at Ames, IA, and Mead, NE, averaged over 1994 and 1995. Regression equations were Ames cut 1, $Y = 43 + 0.58X - 0.00008X^2$, $r^2 = 0.99$, root mean square error (RMSE) = 1.2; Ames cut 2, $Y = 9.5 + 0.063X$, $r^2 = 0.98$, RMSE = 1.1; Mead cut 1, $Y = 80 + 0.19X$, $r^2 = 0.96$, RMSE = 4.8; and Mead cut 2, $Y = 15 + 0.02X$, $r^2 = 0.98$, RMSE = 0.3.

indicated that the N treatments were the single largest source of variation in soil NO_3–N concentrations at both locations (data not shown). Soil NO_3–N levels at the different depths, especially at Mead, showed that switchgrass utilized soil N from the entire profile (Table 4). Biomass yields in 1996 were not related to soil NO_3 levels in the spring, as indicated by nonsignificant regression analyses (Fig. 6). Thus, a spring soil NO_3–N test does not predict switchgrass biomass yields in the Midwest. Berg and Sims (2000) reported a poor relationship between extractable mineral N in the surface 15 cm and herbage mass in fertilized Old World bluestem (*Bothriochloa ischaemum* L.) pastures in Oklahoma. In an evaluation of the effect of different harvest schedules on switchgrass biomass production in Texas, Sanderson et al. (1999) reported plots harvested late in the growing season had lower yields the following spring. In a perennial biomass crop like switchgrass, harvest management in the previous year may have as strong an effect as spring soil NO_3–N levels on unfertilized switchgrass yields in the following year. Perennials such as switchgrass may translocate significant amounts of N to stem bases and roots at the end of the growing season, and this process is likely affected by harvest management.

SUMMARY

In the Midwest, the optimal time to harvest switchgrass for biomass yields is at the 3.3 (R3) to 3.5 (R5) stage of maturity (panicles fully emerged to postanthesis). Maximum first-cut yields are obtained at these growth stages, and depending on the year, sufficient regrowth may be obtained for a second harvest after a killing frost. Whether or not a second harvest is made will depend on biomass yield and price and cost of

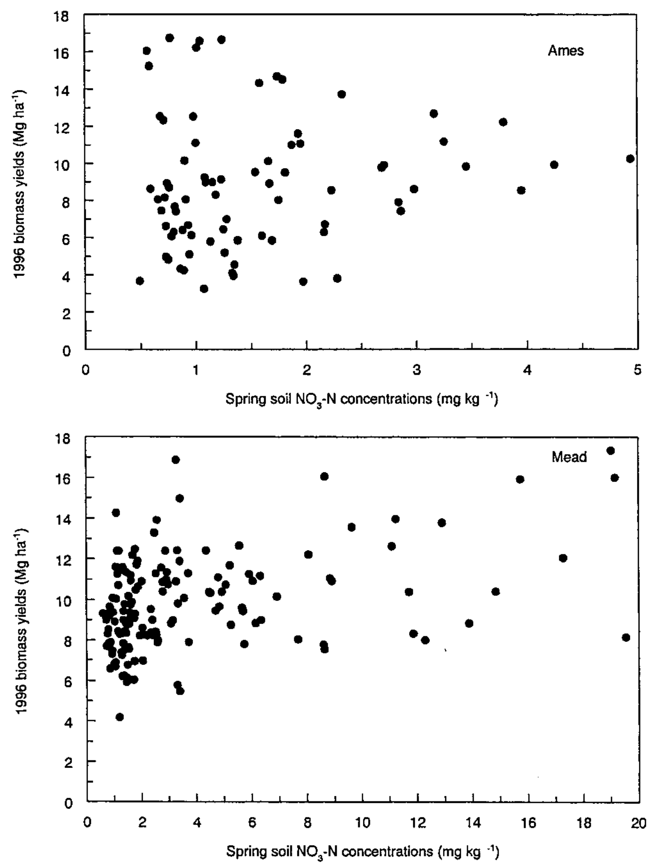

Fig. 6. Response of 1996 switchgrass biomass yields harvested in August to spring 1996 soil NO_3–N concentrations for plots on which harvest and N rate treatments were applied in 1994 and 1995 at Ames, IA, and Mead, NE. Regressions were not significant for either location, with r^2 values of 0.02 and 0.14 for Ames and Mead, respectively.

harvesting. These morphological stages usually occur in the first 3 wk of August for cultivars with the maturity characteristics of Cave-in-Rock or Trailblazer. In terms of time management, this would be a good time for most Midwest farmers because maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] are not ready for harvest and other field work has often been completed by this time. Another potential harvest period would be after a killing frost. Although yields are significantly lower, our results suggest that significant amounts of N are remobilized from the aboveground biomass to stem bases, crowns, or roots of switchgrass plants that are not harvested until after a killing frost. If so, annual N applications may not be needed with this harvest scheme, or N fertilizer levels could be reduced, thus reducing a major input cost. It is not known, however, how much of the stored N is reused the next year. The economic value of reduced fertilizer and application costs would have to exceed the value of the loss in yield. Harvesting after a killing frost could conflict with grain and oilseed crop harvest. Snow is common at this time of year and could complicate harvest. Averaged over years, optimal biomass yields were obtained at the R3 to R5 maturity stages when switchgrass was fertilized with 120 kg N ha^{-1}. At the biomass yield levels obtained (10.6–11.2 Mg ha^{-1} at Mead and 11.6–12.6 Mg ha^{-1} at Ames), the amount of N removed at this fertilization rate was approximately the same as the amount applied. At these yield levels, and at this rate of fertilization, approximately 10 to 12 kg N ha^{-1} needs to be applied for each megagram per hectare of biomass yield.

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