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Switchgrass Response to Harvest Frequency and Time and Rate of Applied Nitrogen[#]

W. E. Thomason,[1,*] W. R. Raun,[2] G. V. Johnson,[2] C. M. Taliaferro,[2] K. W. Freeman,[2] K. J. Wynn,[2] and R. W. Mullen[2]

[1]Samuel Roberts Noble Foundation, Ardmore, Oklahoma, USA
[2]Department of Plant and Soil Science, Oklahoma State University, Stillwater, Oklahoma, USA

ABSTRACT

Switchgrass (*Panicum virgatum* L.) is currently being evaluated as a raw material for producing fuel, chemicals, and electricity. Switchgrass biomass is bound by the growing environment that includes fertility. More information is needed on sustainable switchgrass production as influenced by nitrogen fertility and harvest management. Field experiments were initiated at Chickasha and Perkins, OK in 1996 and 1998, respectively to evaluate switchgrass

[#]Contribution from the Oklahoma Agricultural Experiment Station.
*Correspondence: W. E. Thomason, Virginia Polytechnic Institute and State University, Department of Crop and Soil Environmental Sciences, 422 Smyth Hall, Blacksburg, VA 24061, USA; Fax: 540-231-3075; E-mail: wthomaso@vt.edu.

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response to applied nitrogen (N) at rates of 0, 112, 224, 448, and 896 kg ha^{-1}. In addition, harvest frequency and time of N application were evaluated. Yield maximums and the greatest N, potassium (K), phosphorus (P), and sulfur (S) uptake values were achieved with 448 kg N ha^{-1} applied all in April and harvested three times. In fact, harvest frequency was the most important factor affecting yields over the course of these studies with average dry matter yields of 16.3, 14.7, and 12.9 Mg ha^{-1} yr^{-1} for three, two, and one harvest yr^{-1}, respectively. No significant change in soil organic carbon was detected over time. Although dry matter yields were found to decline with time, total N uptake did not. Forage N concentration was found to be greater in later years, thus increasing production costs. While yields were highest (18.0 Mg ha^{-1}) with 448 kg N ha^{-1} applied all in April and three harvests, applying 0 N and harvesting three times produced almost as much total biomass (16.9 Mg ha^{-1}). This limited response to N is possibly explained by the evolution of switchgrass under low N conditions. Increasing forage concentrations of K, magnesium (Mg), P, and S were noted with increasing yields, indicating a potential for response to these nutrients.

Key Words: Switchgrass; Panicum virgatum; Nitrogen; Biofuel.

INTRODUCTION

Evaluation of switchgrass has shown that it is suitable for use as an energy feedstock, either for producing ethanol, via bioconversion techniques, or electricity via co-firing with coal. It is also being investigated as a replacement for wood pulp in the paper making process. The energy content of switchgrass has been found to be comparable to that of wood and when the expected costs of production are weighed against the value of the crop, switchgrass was capable of producing five times more energy than that required to grow the crop.[1] Analysis of ash and alkali content of switchgrass has shown relatively low alkali levels and therefore should have little slagging potential when used in coal firing systems.[1] This same research noted that due to the high cellulose content, low ash levels, and good fiber length to width ratios, switchgrass could substitute for hardwood pulp in production of high quality paper. Later work estimates the cost of switchgrass production at around \$30 t^{-1} indicating that it would be viable, at least on a cost basis, as a replacement for wood pulp.[2]

Nutrient uptake and loss from production sites are important issues for high-biomass producing crops such as switchgrass. This is especially true if removal, as in haying, and not grazing is practiced. Mineral content of switchgrass has been found to be higher on a percentage scale with lower yields for the macronutrients N, P, K, and calcium (Ca). No change in concentration for many micronutrients has been noted but concentrations of boron (B) and manganese (Mn) have been found to increase with increasing yields.[3] Increases in plant N concentration with increased applied N throughout the season have been noted.[4] Staley et al.[5] found increasing N concentration in harvested plant parts with increases in applied nitrogen. They also found increased N uptake with increased N rates, but only in a one-harvest system. Using ^{15}N as a tracer, they attributed only 15–39% of total N uptake to fertilizer sources but these uptake levels were still above those of tall fescue grown on the same marginal sites. Researchers in Pennsylvania have found N recoveries of 40% of that applied and noted that this number was thought to decrease as native soil N levels increased. Measured on a daily basis, switchgrass has been found to take up 1.49–2.63 $kg\,N\,ha^{-1}\,d^{-1}$.[6] Other research states that if water is not limiting, then N levels account for 80% of the variation in yields. When water is limiting, however, the absence of moisture is the most important factor in yield determination.[7] Depth of soil has been found to have little effect on N uptake.[8]

Harvesting methods involving one to two cuttings each season have been shown to produce optimum yields in most systems.[9] The earlier harvest is usually much higher in animal feed value and a two-cut system may allow early cuttings to be used as livestock feed and later cuttings for biofuel production.[10] Sanderson[11] found that as switchgrass matures through the growing season, stem components increase and leaf components decrease as a percent of total dry biomass. This increase in stem portion is attributed to internode elongation necessary for plant growth and competitiveness.

Switchgrass yields of 10–12 $Mg\,ha^{-1}$ have been reported in Canada.[12] This led the authors to surmise that switchgrass could be a valuable source of biomass for biofuel production. Hall et al.[13] found switchgrass yields in Iowa to be near 6 $Mg\,ha^{-1}$ and noted a consistent response to added N up to 75 $kg\,N\,ha^{-1}$.

Bransby et al.[14] noted switchgrass environmental benefits as an N buffer strip crop and as a net fixer of carbon (C). They state that the most important benefit of using switchgrass as a fuel is the net cycling of C in the environment and give only slight importance to soil C sequestration. Long-term research in Alabama has recently shown no change in soil organic C levels after 3 yrs in continuous switchgrass, but after 10 yrs soil organic C was 45% higher than adjacent fallow ground.[15] The objectives of this study were (1) to evaluate the response in biomass yield and uptake of N, K, P, Ca, Mg, and S of switchgrass grown in Oklahoma to harvest frequency, and time and rate of applied nitrogen and (2) to evaluate the short term effects of switchgrass production on soil organic C levels.

MATERIALS AND METHODS

Two field experiments were initiated to evaluate switchgrass response to applied N at rates of 0, 112, 224, 448, and 896 kg ha^{-1}. In addition, harvest frequency (once at the end of September; twice, mid-July and September; and three times, May, mid-July, and September), and time of N application (all in April; 1/2 in April and 1/2 following first harvest; and 1/3 in April, 1/3 following first harvest, and 1/3 following second harvest) were evaluated (Table 1). Experiments were initiated at Chickasha (Dale silt loam, fine-silty, mixed, superactive, thermic Pachic Haplustoll) and Perkins (Teller sandy loam, fine-loamy, mixed, thermic Udic Arguistoll), OK in 1996 and 1998, respectively. Pre-establishment soil test values and soil classifications for the sites are reported in Table 2. A randomized complete block design with three replications was used at both locations with an incomplete factorial arrangement of treatments (Table 1). The northern lowland switchgrass variety ‘‘Kanlow’’ was broadcast seeded in 1996 at Chickasha and 1998 at Perkins at a rate of 11 kg pure live seed ha^{-1}. The stand at Chickasha was allowed a one-year establishment phase and harvesting began the following spring while Perkins was planted and harvesting begun in the same year. At both sites, preplant rates of 112 kg N ha^{-1}, 224 kg P_2O_5 ha^{-1}, and 560 kg K_2O ha^{-1} were applied to the entire area. Switchgrass was harvested at a height of 10–15 cm using a ‘‘Carter’’ harvester.

Forage samples were dried and ground to pass a 140-mesh sieve (100 um) and analyzed for total N content using a Carlo-Erba NA 1500 automated dry combustion analyzer.[16] Forage samples were also analyzed for tissue concentrations of P, K,[17] Ca, Mg, and S.[18] Nutrient uptake values were calculated by multiplying the yield in kg ha^{-1} by the elemental % in the dry forage.

Surface soil samples (0–15 cm) were taken from both experiments at initiation and analyzed for organic carbon using dry combustion.[16] In spring 2001, bulk density samples were taken with a Giddings soil probe from the experimental area and an adjacent area that was conventionally tilled for comparison. Also in spring 2001, surface soil samples (0–15 cm) samples were taken between plant crowns to simulate the initial sampling and also from within the crown of the plant to evaluate sampling methods. Soil organic carbon levels (mg C cm^{-2}) were calculated as

Table 1. Treatment structure for switchgrass experiment, Chickasha (initiated 1996) and Perkins (initiated 1998).

Trt.	N rate	N application method	# of harvests
1	0	—	One
2	0	—	Two
3	0	—	Three
4	112	All in April	One
5	224	All in April	One
6	448	All in April	One
7	896	All in April	One
8	112	All in April	Two
9	224	All in April	Two
10	448	All in April	Two
11	896	All in April	Two
12	112	All in April	Three
13	224	All in April	Three
14	448	All in April	Three
15	896	All in April	Three
16	112	1/2 in April, 1/2 aft. 1st harvest	Two
17	224	1/2 in April, 1/2 aft. 1st harvest	Two
18	448	1/2 in April, 1/2 aft. 1st harvest	Two
19	896	1/2 in April, 1/2 aft. 1st harvest	Two
20	112	1/3 in April, 1/3 aft. 1st harv., 1/3 aft 2nd harv	Three
21	224	1/3 in April, 1/3 aft. 1st harv., 1/3 aft 2nd harv	Three
22	448	1/3 in April, 1/3 aft. 1st harv., 1/3 aft 2nd harv	Three
23	896	1/3 in April, 1/3 aft. 1st harv., 1/3 aft 2nd harv	Three

a product of bulk density ($g\,soil\,cm^{-3}$), core depth (cm), and soil carbon concentration ($mg\,C\,g^{-1}$ soil).

Statistical evaluation and analysis of variance were performed using SAS.[19]

RESULTS

Chickasha

The Chickasha site was the only one established in time for the 1997 summer harvests. Central Oklahoma received timely and adequate rainfall throughout the summer and maximum production levels were in excess of $30\,Mg\,ha^{-1}$ (Table 3). Three harvests, one early in the

Table 2. Initial soil chemical characteristics (0–15 cm) and classification at Chickasha and Perkins, OK.

Location	pH[a]	NH_4-N	NO_3-N	P[b]	K[b]	Total N[c]	Organic C[c]	D_b initial	D_b 2001
		(mg kg^{-1})				(mg g^{-1})		(g cm^{-3})	
Chickasha	6.9	7.58	11.2	28	215	0.06	8.2	1.43	1.41
Classification: Dale silt loam (fine-silty, mixed, superactive, thermic Pachic Haplustoll)									
Perkins	6.7	7.53	2.1	77	325	0.9	6.8	1.47	1.47
Classification: Teller sandy loam (fine-loamy, mixed, active, thermic Udic Argiustoll)									

D_b: bulk density (g cm^{-3}).
[a]pH: 1:1 soil:water.
[b]P and K: Mehlich III.
[c]Organic C and total N: dry combustion.

summer, one in late summer and one at the end of the season, produced more biomass (27.7 Mg ha^{-1}) compared to one harvest at the end of the season (18.6 Mg ha^{-1}). These results reflect the ideal weather conditions present in 1997 that resulted in high yields. Three harvests resulted in higher N uptake values than those with fewer cuttings, even when yields were higher for plots with fewer cutting dates (Table 3). The lowest N uptake values for any treatment occurred with lower N rates (less than 224 kg ha^{-1}) and one or two cuttings. Three harvests increased K uptake by the plants and split-applying the N over three dates resulted in more K uptake than with two N application dates. Neither treatment removed as much K as those with all N applied in April. This is plausible considering the amount of K removed in the stems. Phosphorus uptake levels were, on average, approximately ten times lower than N or K uptake levels. This was expected based on previous work documenting N:P ratios of 10:1.[20] Splitting N applications over two dates resulted in lower P removal than when applying all N early in the season (Table 3).

In 1998, a significant response to applied N was observed. However, no differences in harvest frequency were noted, probably due to the lack of rainfall in mid-summer. Total yields were much lower than in 1997. Lower rates of early season N and the removal of forage in late-summer decreased yields in plots with three harvests and three-way split N applications when compared to those cut twice. Although yields were lower in 1998, maximum N uptake was higher than 1997 (375 and 330 kg ha^{-1}, respectively). There was no difference in N uptake until total N rates reached 224 kg ha^{-1}. Potassium uptake values were found to follow the same trend as N. Maximum K uptake occurred with three-harvests and lowest values with one-harvest (Table 4).

Yields were again high at the Chickasha site in 1999 with some plots producing over 20 Mg ha^{-1} (Table 5). The average yield for the site was 17 Mg ha^{-1}. The highest levels of N uptake were observed with split applications of N and multiple harvests. Uptake of K mirrored that for N in that number of harvests was highly significant and multiple harvests tended to remove more K than one harvest. Phosphorus uptake was greatest for three harvests regardless of N timing. (35.3 and 15.4 kg ha^{-1} for three and one harvest, respectively).

Yields for 2000 represent only the first two scheduled harvests for the year and not the final, end of season, harvest. Due to heavy fall rains, harvest was delayed and due to lack of communication, the area was burned before the final harvest could be taken. Therefore, yields shown in Table 6 represent the sum of only two cuttings. The highest yields were cut two times (scheduled for three) and either not fertilized or fertilized at the lowest rate of 112 kg N ha^{-1} (15.4 and 15.7 Mg ha^{-1}). Nitrogen

Table 3. Analysis of variance and means for total dry matter yield, N uptake, K uptake, P uptake, Ca uptake, Mg uptake, and S uptake, for switchgrass produced under variable rates and harvest frequency, Chickasha, OK, 1997.

		Yield	N uptake	K uptake	P uptake	Ca uptake	Mg uptake	S uptake
Source of variation	df				(mean squares)			
Replication	2	3850.1	1094.1	2807.2	25.8	44.1	149.1	19.1
Cutting	2	413232.9[b]	70944.3[b]	134488.2[b]	623.6[b]	980.9	1123.4[b]	478.9[b]
N timing	3	36187.3	1053.5	3790.8	13.4	3.0	1.9	5.8
N rate	3	156470.8[a]	20920.8[a]	17108.8[a]	153.33	260.5	255.7	53.4[a]
Cutting[a] N rate	8	70785.9	5621.6	2638.7	39.3	152.6	216.6	30.2
N timing[a] N rate	6	65107.4	4164.4	6009.1	52.7	123.2	203.1	31.4
Residual error	44	47895.3	3820.7	5208.8	47.3	192.4	191.7	28.8
Total N rate (kg ha^{-1})	Cut/timing	(Mg ha^{-1})			(kg ha^{-1})			
0	1 harvest	22.2	165.0	168.9	19.5	38.6	40.0	13.1
112	1 harvest	17.4	117.7	124.7	13.4	33.7	37.2	10.4
224	1 harvest	16.4	140.6	128.5	15.4	28.4	31.0	10.0
448	1 harvest	16.9	118.6	131.1	13.5	32.2	35.2	10.5
896	1 harvest	20.3	154.1	148.9	17.3	39.4	39.0	12.7
0	2 harvests	33.4	254.8	261.2	29.6	55.2	60.0	20.8
112	2 harvests	15.5	153.6	152.1	16.1	40.3	34.4	11.8

224	2 harvests	33.7	282.5	269.4	28.4	64.3	68.8	22.2
448	2 harvests	29.6	283.0	284.2	31.0	53.1	58.9	20.6
896	2 harvests	24.4	231.1	233.7	21.7	40.3	46.4	16.3
0	3 harvests	26.7	232.5	313.6	26.7	52.0	59.4	18.2
112	3 harvests	24.9	215.1	290.2	24.4	34.8	38.9	19.3
224	3 harvests	27.7	260.8	335.8	29.3	42.0	43.2	23.7
448	3 harvests	30.9	300.0	381.4	33.3	42.5	47.3	26.5
896	3 harvests	28.6	320.2	327.5	26.8	42.0	44.9	25.0
112	2-sp N, 2 harv	24.1	203.7	197.6	21.6	42.0	49.0	16.0
224	2-sp N, 2 harv	25.3	209.1	195.8	21.9	48.2	49.2	16.2
448	2-sp N, 2 harv	36.7	330.6	341.3	38.2	62.6	69.1	24.3
896	2-sp N, 2 harv	20.2	195.0	171.4	21.2	41.6	42.4	14.8
112	3-sp N, 3 harv	24.7	210.1	267.7	23.7	35.4	41.6	22.0
224	3-sp N, 3 harv	19.9	182.1	219.1	20.2	32.2	34.2	16.4
448	3-sp N, 3 harv	31.8	214.5	368.7	32.5	49.0	48.5	25.1
896	3-sp N, 3 harv	29.1	273.9	341.1	31.3	43.3	46.9	25.4
SED		5.7	50.5	58.9	5.3	11.3	11.3	4.4

SED—standard error of the difference between two equally replicated means.
2-sp N, 2 harv—2 harvest system, N applied in April and after first harvest.
3-sp N, 3 harv—3 harvest system, N applied in April and after each of the first two harvests.
[a,b]Significant at the 0.05 and 0.01 probability level, respectively.

Table 4. Analysis of variance and means for total dry matter yield, N uptake, K uptake, P uptake, Ca uptake, Mg uptake, and S uptake, for switchgrass produced under variable rates and harvest frequency, Chickasha, OK, 1998.

		Yield	N uptake	K uptake	P uptake	Ca uptake	Mg uptake	S uptake
Source of variation	df				(mean squares)			
Replication	2	99653.9[a]	8760.0	20505.3[a]	63.6	927.8	1553.6	101.0
Cutting	2	37203.5	41409.6[a]	65317.7[b]	102.4	100.9	156.3	26.6
N timing	3	57619.6	11101.8	18577.4[a]	93.6	489.5	634.4	80.4
N rate	3	81157.5[a]	3300.3	6267.6[a]	52.7[a]	458.4[a]	587.2	33.6[a]
Cutting[a] N rate	8	23906.8	5937.6	6420.5	40.0	602.8	1043.3	56.0
N timing[a] N rate	6	16868.4	3459.7	4353.2	18.0	262.4	717.2	28.2
Residual error	44	22058.1	5046.0	5210.9	41.2	333.8	400.5	31.8
Total N rate (kg ha^{-1})	Cut/timing	(Mg ha^{-1})			(kg ha^{-1})			
0	1 harvest	16.6	204.8	190.2	22.1	68.9	59.2	18.0
112	1 harvest	14.1	178.0	187.5	19.5	60.1	63.8	16.4
224	1 harvest	15.8	212.7	211.9	20.7	69.8	66.8	18.3
448	1 harvest	17.2	217.0	221.2	21.1	72.6	74.7	20.0
896	1 harvest	10.0	132.8	125.6	11.7	43.4	43.0	11.4
0	2 harvests	16.6	223.2	246.8	22.5	67.7	77.6	20.5
112	2 harvests	11.2	154.8	161.0	16.9	43.6	43.8	12.4
224	2 harvests	22.6	300.0	337.8	31.1	91.0	104.6	27.7

448	2 harvests	14.7	195.6	185.5	18.7	30.9	30.0	9.8
896	2 harvests	16.2	226.5	224.1	19.1	57.5	68.0	19.0
0	3 harvests	21.5	340.3	347.3	28.0	67.1	81.9	22.8
112	3 harvests	16.8	235.2	270.5	20.1	53.3	65.8	18.4
224	3 harvests	20.5	283.3	343.2	25.3	61.6	71.6	20.5
448	3 harvests	24.5	375.6	386.4	28.9	64.1	66.8	19.0
896	3 harvests	14.7	222.9	237.7	18.9	48.7	53.7	16.5
112	2-sp N, 2 harv	17.5	211.9	245.5	24.7	61.4	75.7	21.3
224	2-sp N, 2 harv	20.0	267.7	312.3	28.9	77.7	84.6	25.8
448	2-sp N, 2 harv	15.8	207.0	246.4	21.2	60.1	72.5	20.0
896	2-sp N, 2 harv	15.6	235.5	220.7	22.0	62.1	60.9	20.1
112	3-sp N, 3 harv	14.1	196.2	211.0	16.4	42.5	52.2	14.0
224	3-sp N, 3 harv	14.6	223.3	222.8	18.3	52.0	56.7	16.9
448	3-sp N, 3 harv	17.5	237.5	273.9	21.9	53.1	61.9	17.2
896	3-sp N, 3 harv	13.5	221.0	237.6	17.2	46.3	53.4	16.2
SED		1.2	58.0	58.9	5.2	14.9	16.3	4.6

SED—standard error of the difference between two equally replicated means.
2-sp N, 2 harv—2 harvest system, N applied in April and after first harvest.
3-sp N, 3 harv—3 harvest system, N applied in April and after each of the first two harvests.
[a,b]Significant at the 0.05 and 0.01 probability level, respectively.

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Table 5. Analysis of variance and means for total dry matter yield, N uptake, K uptake, P uptake, Ca uptake, Mg uptake, and S uptake, for switchgrass produced under variable rates and harvest frequency, Chickasha, OK, 1999.

		Yield	N uptake	K uptake	P uptake	Ca uptake	Mg uptake	S uptake
Source of variation	df				(mean squares)			
Replication	2	46442.3	86590.6	110207.0[a]	1300.8[a]	166.5	696.1[a]	29.1
Cutting	2	4510.1	95291.8[a]	103887.7[b]	1429.0[b]	13.9	20.9	220.3[b]
N timing	3	12013.7	13320.8	13466.6	109.1	323.0	227.4	78.9[a]
N rate	3	243068.7	71751.7	59600.7	421.5	179.9	250.0	10.2
Cutting[a] N rate	8	20749.0	2810.1	4365.8	25.0	446.5[b]	466.7[a]	38.0
N timing[a] N rate	6	206059.5	49314.0	38090.3	344.4	81.0	120.7	15.9
Residual error	44	156273.7	39129.9	33467.5	350.4	149.1	180.8	29.1
Total N rate ($kg\,ha^{-1}$)	Cut/timing	($Mg\,ha^{-1}$)			($kg\,ha^{-1}$)			
0	1 harvest	10.9	78.1	101.1	12.4	32.8	38.0	9.3
112	1 harvest	15.0	157.7	154.1	17.1	47.8	53.2	14.5
224	1 harvest	16.2	145.9	195.4	18.9	43.6	58.1	13.1
448	1 harvest	19.1	180.0	238.6	18.1	69.3	71.5	18.0
896	1 harvest	11.4	125.7	109.5	10.4	34.5	36.3	9.8
0	2 harvests	17.9	227.8	273.6	27.4	54.3	60.2	19.2
112	2 harvests	13.2	175.4	223.7	21.1	41.6	43.2	14.9
224	2 harvests	17.0	221.0	245.3	24.4	53.0	61.4	18.2

448	2 harvests	16.2	217.2	229.1	22.1	35.2	40.0	12.0
896	2 harvests	17.3	247.4	251.4	21.6	53.4	58.4	18.0
0	3 harvests	20.0	275.0	327.3	35.2	50.0	55.9	20.5
112	3 harvests	18.5	315.0	345.0	37.9	53.3	51.5	24.9
224	3 harvests	16.7	278.7	330.3	33.5	39.2	43.6	18.4
448	3 harvests	19.1	330.0	349.1	36.8	48.0	53.0	20.7
896	3 harvests	15.4	285.7	300.0	33.1	43.1	47.2	19.4
112	2-sp N, 2 harv	14.5	179.4	225.8	22.6	43.2	46.9	15.6
224	2-sp N, 2 harv	14.6	180.8	207.8	22.3	56.4	50.1	19.5
448	2-sp N, 2 harv	17.5	218.1	271.3	24.8	48.7	55.7	17.1
896	2-sp N, 2 harv	20.8	270.2	355.7	28.8	65.4	70.3	22.0
112	3-sp N, 3 harv	15.5	222.0	252.2	26.0	35.3	38.1	14.5
224	3-sp N, 3 harv	15.2	250.1	294.9	30.4	41.2	40.1	17.4
448	3-sp N, 3 harv	18.0	270.7	313.7	35.4	40.5	47.5	17.0
896	3-sp N, 3 harv	26.3	332.8	314.4	42.5	36.6	40.1	16.7
SED		10.2	157.3	149.4	15.3	10.0	11.0	3.8

SED—standard error of the difference between two equally replicated means.
2-sp N, 2 harv—2 harvest system, N applied in April and after first harvest.
3-sp N, 3 harv—3 harvest system, N applied in April and after each of the first two harvests.
[a,b]Significant at the 0.05 and 0.01 probability level, respectively.

Table 6. Analysis of variance and means for total dry matter yield, N uptake, K uptake, P uptake, Ca uptake, Mg uptake, and S uptake, for switchgrass produced under variable rates and harvest frequency, Chickasha, OK, 2000.

		Yield	N uptake	K uptake	P uptake	Ca uptake	Mg uptake	S uptake
Source of variation	df				(mean squares)			
Replication	2	19482.3[b]	3576.9[a]	2339.1	149.7[b]	115.1	296.9[b]	24.0[a]
Cutting	2	32537.0[b]	72733.9[b]	144564.1[b]	945.1[b]	297.8[b]	160.2	76.9[b]
N timing	3	1897.9[a]	1027.9	1572.3	6.0	66.3	38.0	2.8
N rate	3	13173.0[b]	1323.7	2492.8	76.5	34.4	186.5[a]	12.4
Cutting[a] N rate	8	7423.6[a]	3248.4[a]	2909.6	49.1	126.8[a]	121.3	10.5
N timing[a] N rate	6	2957.4	776.2	2634.1	38.4	23.7	23.9	4.1
Residual error	44	3124.4	826.3	1660.2	15.7	35.2	38.5	5.2
Total N rate (kg ha^{-1})	Cut/timing	(Mg ha^{-1})			(kg ha^{-1})			
0	1 harvest	—	—	—	—	—	—	—
112	1 harvest	—	—	—	—	—	—	—
224	1 harvest	—	—	—	—	—	—	—
448	1 harvest	—	—	—	—	—	—	—
896	1 harvest	—	—	—	—	—	—	—
0	2 harvests	14.0	149.3	192.3	21.7	32.0	43.9	13.2
112	2 harvests	11.0	125.2	151.6	20.3	26.4	34.5	10.6
224	2 harvests	12.5	133.4	194.2	19.3	27.7	41.8	10.9

448	2 harvests	11.7	148.5	123.2	18.5	26.4	36.1	11.4
896	2 harvests	10.2	150.9	121.7	15.2	31.5	33.8	10.4
0	3 harvests	15.4	256.4	317.7	31.7	38.9	48.1	17.1
112	3 harvests	15.7	256.0	331.7	34.7	38.7	50.7	17.0
224	3 harvests	14.1	247.7	318.3	33.6	37.6	43.4	17.7
448	3 harvests	15.4	271.9	308.4	34.2	38.4	45.1	18.0
896	3 harvests	9.2	167.6	201.2	17.0	21.8	25.8	11.0
112	2-sp N, 2 harv	10.3	112.3	126.2	16.7	22.5	31.9	9.7
224	2-sp N, 2 harv	12.5	126.5	146.8	19.2	28.2	40.4	10.8
448	2-sp N, 2 harv	10.7	121.2	135.0	18.5	23.2	35.3	9.8
896	2-sp N, 2 harv	10.6	141.9	149.0	16.4	26.0	32.5	10.1
112	3-sp N, 3 harv	13.9	223.8	276.2	28.0	34.6	41.8	15.4
224	3-sp N, 3 harv	12.0	219.4	247.4	26.8	28.1	36.1	14.5
448	3-sp N, 3 harv	14.4	250.4	305.3	33.6	33.8	44.1	17.8
896	3-sp N, 3 harv	11.2	201.3	242.7	25.9	25.3	29.7	13.4
SED		1.4	23.5	33.3	3.2	4.9	5.1	1.9

SED—standard error of the difference between two equally replicated means.
2-sp N, 2 harv—2 harvest system, N applied in April and after first harvest.
3-sp N, 3 harv—3 harvest system, N applied in April and after each of the first two harvests.
[a,b]Significant at the 0.05 and 0.01 probability level, respectively.

uptake of 240 kg N ha^{-1} was highest for two harvests (scheduled for three) and April fertilization (Table 6). Potassium uptake was highest with multiple harvests. The lack of the final harvest for this data set severely limited interpretation.

Perkins

Yields in 1998 were lower than those at Chickasha due to sandier soil and less total rainfall. Treatment combinations with two or three harvests and split N applications produced the highest yields, averaging over 11 Mg ha^{-1}. Forage nitrogen concentration did not increase with increasing yields, as was the trend over all years (Fig. 1). Potassium uptake was maximized with two harvests, and either one or two N applications, both averaging near 180 kg K ha^{-1}. Uptake of P was significantly affected by N rate and was greatest with one harvest and one N application date at 17.4 kg ha^{-1} (Table 7). Phosphorus uptake decreased with multiple harvests.

Perkins again produced much lower yields than Chickasha in 1999 and significant differences were noted due to number of harvests and N timing (Table 8). Average yields were highest for the three harvests, three-way split N treatments (Table 8). Multiple harvests increased crop N uptake over those with the same total N rates and one harvest. Potassium uptake was high for all multiple harvest plots. In fact, one harvest

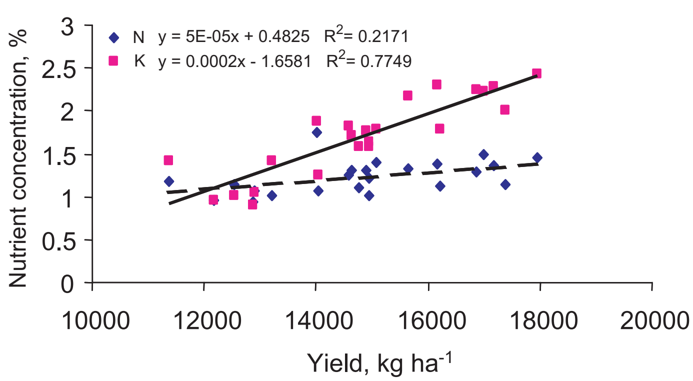

Figure 1. N and K concentrations with increasing dry biomass yields, Chickasha and Perkins. *(View this art in color at www.dekker.com.)*

removed little more than half of the K of two or three harvests (77.5 vs. 155.2 $kg\,ha^{-1}$). Three harvests also resulted in increased P uptake.

Dry matter yield in 2000 averaged over N rate was 13.3 $Mg\,ha^{-1}$ (Table 9). Nitrogen removal was maximized with three harvests and splitting N into three applications (Table 9). There was a trend toward increased N uptake with increasing harvest frequency and increasing N rate. Three harvests with N split into three increments resulted in 48% more K uptake than two harvests and two N application dates (89.6 vs. 184.4 $kg\,ha^{-1}$). The highest average P uptake was found for three harvests and three-way split N applications (20.2 $kg\,ha^{-1}$) (Table 9).

Soil Carbon

Organic C data from in crown and between crown samples were compared to organic C from initial samples from the area to determine if changes had occurred. Bulk density measurements taken from the experimental area did not differ from an adjacent area that was conventionally tilled. Initial samples indicated average soil organic C (SOC) for the site of 6.8 and 8.2 $mg\,g^{-1}$ for Perkins and Chickasha, respectively. These results are possibly confounded by known spatial variability in SOC reported by Raun et al.[21] Contrast comparisons found a significant linear decrease in SOC with increasing N rates and two harvests for the Chickasha crown sampling (Table 10). A significant quadratic increase was noted for Perkins in crown samples and a significant quadratic decrease in SOC with increasing N rate was found for between crown samples at Chickasha. Taken together, there seem to be no obvious trends toward increasing or decreasing SOC at either site. This is potentially influenced by the fact that aboveground biomass was removed from the site. Garten and Wullschleger[22] have estimated that it may take a decade of switchgrass production to sequester a significant, measurable amount of soil carbon. Given more time, SOC may increase, but the short duration (3–5 yrs) of this study has provided no real evidence supporting this increase in SOC, especially in the ‘‘between crown’’ samples.

CONCLUSIONS

Overall forage K concentrations increased with increasing yield, while N concentrations were not affected (Fig. 1). This suggests an increased likelihood of obtaining a response to K rather than N in

Table 7. Analysis of variance and means for total dry matter yield, N uptake, K uptake, P uptake, Ca uptake, Mg uptake, and S uptake, for switchgrass produced under variable rates and harvest frequency, Perkins, OK, 1998.

		Yield	N uptake	K uptake	P uptake	Ca uptake	Mg uptake	S uptake
Source of variation	df				(mean squares)			
Replication	2	7364.9	3547.8	7004.5[b]	296.2[b]	1843.0[b]	221.5[a]	15.1
Cutting	2	3988.9	13770.8	10259.9[b]	39.2	1.8	139.8	5.6
N timing	3	106.2	15131.9	773.4	7.6	481.8	10.5	1.4
N rate	3	11878.2[a]	20266.0	4776.4	15.7[a]	192.5	104.5	18.4
Cutting[a] N rate	8	5048.9	9275.1	2172.9[a]	16.4	287.5	146.6	16.5
N timing[a] N rate	6	2239.1	21785.9	2191.6	18.9	345.3	134.4	16.1
Residual error	44	2867.9	17347.7	1232.9	9.4	200.4	62.0	11.2
Total N rate ($kg\,ha^{-1}$)	Cut/timing	($Mg\,ha^{-1}$)			($kg\,ha^{-1}$)			
0	1 harvest	10.6	188.9	97.2	16.2	44.2	26.1	14.7
112	1 harvest	8.4	123.9	105.8	13.6	57.7	26.8	12.4
224	1 harvest	10.2	181.2	103.3	17.3	44.8	27.6	14.5
448	1 harvest	11.9	197.0	153.0	17.7	53.5	32.6	16.6
896	1 harvest	10.4	234.9	184.0	22.2	52.2	32.3	17.8
0	2 harvests	8.7	111.0	128.3	11.2	33.0	25.7	11.0
112	2 harvests	10.3	159.6	166.2	13.9	53.4	35.0	14.7

224	2 harvests	13.3	208.2	217.7	17.7	60.8	47.1	18.8
448	2 harvests	11.0	187.4	186.1	13.3	28.5	23.2	10.4
896	2 harvests	10.9	204.1	208.5	15.4	68.5	41.6	17.0
0	3 harvests	12.1	167.7	172.8	17.0	49.5	39.3	14.3
112	3 harvests	11.1	167.8	152.3	12.9	43.1	36.6	13.1
224	3 harvests	10.7	176.7	171.1	13.7	46.1	34.1	14.0
448	3 harvests	12.4	203.8	162.0	13.5	40.0	31.8	13.6
896	3 harvests	10.4	216.6	164.7	14.4	47.3	31.2	14.8
112	2-sp N, 2 harv	9.8	128.2	145.5	11.6	42.3	30.8	12.7
224	2-sp N, 2 harv	11.8	171.3	186.1	14.1	64.8	38.6	17.0
448	2-sp N, 2 harv	11.8	186.1	199.5	14.3	53.7	39.3	16.7
896	2-sp N, 2 harv	11.9	218.3	183.8	14.5	48.6	34.6	16.8
112	3-sp N, 3 harv	11.5	186.8	166.2	15.1	51.4	34.1	13.6
224	3-sp N, 3 harv	10.9	493.3	156.4	13.5	60.3	32.9	13.0
448	3-sp N, 3 harv	14.0	210.1	226.6	19.3	64.7	43.7	16.1
896	3-sp N, 3 harv	9.0	153.0	109.9	9.1	53.1	29.5	11.4
SED		1.4	107.5	28.7	2.5	11.6	6.4	2.7

SED—standard error of the difference between two equally replicated means.
2-sp N, 2 harv—2 harvest system, N applied in April and after first harvest.
3-sp N, 3 harv—3 harvest system, N applied in April and after each of the first two harvests.
[a,b]Significant at the 0.05 and 0.01 probability level, respectively.

Table 8. Analysis of variance and means for total dry matter yield, N uptake, K uptake, P uptake, Ca uptake, Mg uptake, and S uptake, for switchgrass produced under variable rates and harvest frequency, Perkins, OK, 1999.

		Yield	N uptake	K uptake	P uptake	Ca uptake	Mg uptake	S uptake
Source of variation	df				(mean squares)			
Replication	2	3011.2	972.8	5763.7	28.3	104.9	24.4	2.4
Cutting	2	11122.2[a]	13090.2[b]	26238.5[b]	150.2[b]	269.4	45.7	41.8[b]
N timing	3	3182.8[a]	2676.1[b]	4336.7[b]	11.7	33.6[b]	20.4[b]	5.0
N rate	3	7138.1	4824.8[b]	5692.7[b]	3.7	31.9[a]	140.4[a]	12.2
Cutting[a] N rate	8	3610.0	697.3	1574.5[a]	10.5	53.6	17.8	2.7
N timing[a] N rate	6	3164.7	1242.8	806.4	11.7	73.0	29.4	5.0
Residual error	44	7436.4	1626.1	1694.8	13.4	99.0	43.2	7.9
Total N rate ($kg\,ha^{-1}$)	Cut/timing	($Mg\,ha^{-1}$)			($kg\,ha^{-1}$)			
0	1 harvest	7.0	37.9	49.4	8.5	19.7	12.3	4.4
112	1 harvest	9.7	81.3	70.0	12.2	33.1	17.1	7.8
224	1 harvest	7.2	68.4	61.4	7.1	23.2	15.9	6.0
448	1 harvest	9.1	98.4	92.5	7.9	27.6	21.2	7.9
896	1 harvest	10.5	120.2	114.2	8.2	31.6	23.7	9.2
0	2 harvests	5.2	38.8	66.1	6.5	19.1	9.3	4.2
112	2 harvests	8.8	80.4	138.7	12.7	35.7	17.9	8.0
224	2 harvests	10.3	120.9	181.9	13.6	32.1	24.9	9.8

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448	2 harvests	10.1	125.5	180.9	11.3	22.7	20.6	7.3
896	2 harvests	12.0	160.3	208.3	11.9	34.4	26.6	10.8
0	3 harvests	8.7	101.9	113.3	12.7	30.7	15.1	7.9
112	3 harvests	9.6	113.3	147.6	15.2	36.5	21.1	10.1
224	3 harvests	10.1	125.8	130.0	15.2	41.1	20.8	11.0
448	3 harvests	10.7	153.2	150.5	14.8	34.1	23.8	10.0
896	3 harvests	12.8	205.8	174.7	17.4	32.9	26.7	12.7
112	2-sp N, 2 harv	6.9	48.0	90.7	7.5	23.3	11.5	4.9
224	2-sp N, 2 harv	8.8	88.9	130.9	10.8	31.0	19.8	7.8
448	2-sp N, 2 harv	9.9	104.5	155.4	10.9	32.2	25.6	8.9
896	2-sp N, 2 harv	11.9	130.6	190.0	13.3	34.5	26.9	10.2
112	3-sp N, 3 harv	10.4	98.6	108.7	14.9	27.4	17.4	8.6
224	3-sp N, 3 harv	12.6	160.8	154.7	17.8	39.8	22.7	11.4
448	3-sp N, 3 harv	10.9	153.1	143.1	12.6	34.4	23.0	10.5
896	3-sp N, 3 harv	10.9	143.4	144.1	13.7	30.4	20.9	10.0
SED		2.2	32.9	11.4	3.0	8.1	5.4	2.3

SED—standard error of the difference between two equally replicated means.
2-sp N, 2 harv—2 harvest system, N applied in April and after first harvest.
3-sp N, 3 harv—3 harvest system, N applied in April and after each of the first two harvests.
[a,b]Significant at the 0.05 and 0.01 probability level, respectively.

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Table 9. Analysis of variance and means for total dry matter yield, N uptake, K uptake, P uptake, Ca uptake, Mg uptake, and S uptake, for switchgrass produced under variable rates and harvest frequency, Perkins, OK, 2000.

		Yield	N uptake	K uptake	P uptake	Ca uptake	Mg uptake	S uptake
Source of variation	df			(mean squares)				
Replication	2	49718.3[b]	1697.1	19364.5[b]	45.9[a]	176.4[a]	159.5[a]	12.7
Cutting	2	33697.7[a]	19861.3[b]	105277.4[b]	637.8[b]	51.0	858.2[b]	78.9[b]
N timing	3	3036.4	3950.8[a]	10944.8[a]	49.9[a]	69.7[a]	27.6	20.3
N rate	3	9226.3	5870.9[b]	84.6	4.1	110.4[a]	97.3[a]	18.0[a]
Cutting[a] N rate	8	2537.9	4753.5[b]	6523.1[a]	56.9[b]	152.7	89.9[b]	23.3[b]
N timing[a] N rate	6	1382.6	3744.0[b]	4657.3	32.7	66.3	62.9[a]	16.0[a]
Residual error	44	4769.6	928.2	1922.7	14.0	38.5	38.5	5.1
Total N rate ($kg\,ha^{-1}$)	Cut/timing	($Mg\,ha^{-1}$)			($kg\,ha^{-1}$)			
0	1 harvest	9.9	43.6	66.2	3.9	19.5	7.0	4.4
112	1 harvest	8.5	47.9	69.7	3.3	21.4	6.5	4.4
224	1 harvest	11.7	81.0	108.1	5.6	27.7	9.9	7.9
448	1 harvest	9.9	83.5	132.2	5.2	27.0	10.3	6.6
896	1 harvest	12.6	97.7	129.6	4.8	33.6	12.4	7.8
0	2 harvests	9.1	54.3	92.1	11.1	23.3	14.6	6.1
112	2 harvests	9.6	94.1	132.0	11.8	27.1	18.8	7.2
224	2 harvests	12.2	113.0	154.7	14.2	35.5	26.9	9.4

448	2 harvests	11.2	106.9	127.0	12.6	31.1	23.9	8.1
896	2 harvests	13.2	139.8	170.9	12.4	30.4	27.2	9.0
0	3 harvests	13.7	139.1	192.8	23.2	31.0	23.4	12.5
112	3 harvests	12.9	148.0	195.4	20.2	34.2	25.9	12.2
224	3 harvests	13.2	178.9	198.2	20.2	34.7	27.6	13.3
448	3 harvests	12.5	194.8	207.3	19.1	27.9	24.1	12.0
896	3 harvests	14.3	55.5	51.8	4.8	13.0	11.1	3.8
112	2-sp N, 2 harv	9.5	59.9	97.3	12.2	25.2	15.8	6.2
224	2-sp N, 2 harv	10.6	86.5	86.7	13.7	36.7	21.8	8.2
448	2-sp N, 2 harv	11.2	114.7	84.9	12.8	33.3	26.8	9.1
896	2-sp N, 2 harv	11.5	118.6	89.5	12.5	32.1	26.4	9.1
112	3-sp N, 3 harv	12.0	133.4	168.1	20.7	29.5	21.2	10.9
224	3-sp N, 3 harv	12.8	175.9	196.7	21.1	35.3	25.1	13.4
448	3-sp N, 3 harv	13.5	204.8	187.5	20.1	34.2	27.5	14.8
896	3-sp N, 3 harv	13.1	187.9	185.4	18.8	29.8	25.3	12.6
SED		1.8	24.9	35.8	3.1	4.9	4.9	1.9

SED—standard error of the difference between two equally replicated means.
2-sp N, 2 harv—2 harvest system, N applied in April and after first harvest.
3-sp N, 3 harv—3 harvest system, N applied in April and after each of the first two harvests.
[a,b]Significant at the 0.05 and 0.01 probability level, respectively.

Table 10. Surface soil sample (0–15 cm) organic C between crowns of plants and within crowns, Chickasha and Perkins, OK, 2001.

Total N rate ($kg\,ha^{-1}$)	Harvest/N timing	Chickasha (in crown)	Chickasha (between crown)	Perkins (in crown)	Perkins (between crown)
		($mg\,C\,cm^{-1}$)			
0	1 harvest	191.38	197.31	197.26	167.12
112	1 harvest	166.55	188.78	207.24	174.62
224	1 harvest	209.67	235.83	199.90	159.08
448	1 harvest	207.14	214.31	177.52	165.24
896	1 harvest	214.57	223.02	224.55	176.33
0	2 harvests	176.07	218.56	204.74	136.09
112	2 harvests	182.85	189.97	184.39	167.41
224	2 harvests	202.62	207.27	182.29	148.99
448	2 harvests	178.77	207.66	162.90	139.42
896	2 harvests	217.88	157.22	216.75	175.39
0	3 harvests	190.18	178.43	180.51	146.27
112	3 harvests	198.23	172.94	205.47	161.11
224	3 harvests	208.44	200.76	180.89	149.54
448	3 harvests	246.17	193.27	196.90	150.79
896	3 harvests	185.79	187.47	189.95	158.93
112	2 sp N, 2 harv	152.68	183.32	199.82	164.74
224	2 sp N, 2 harv	215.17	194.20	171.89	152.61
448	2 sp N, 2 harv	204.03	214.03	181.55	144.17
896	2 sp N, 2 harv	157.70	156.24	215.19	175.36
112	3 sp N, 3 harv	170.95	183.35	180.21	143.97
224	3 sp N, 3 harv	200.21	182.63	193.81	168.24
448	3 sp N, 3 harv	197.21	197.23	187.91	156.82
896	3 sp N, 3 harv	207.79	176.55	191.63	151.57
SED		66.23	66.93	54.62	55.31
Mean		194.87	193.93	192.75	157.99
Contrasts					
1 harvest					
N rate linear		ns	ns	ns	ns
N rate quad		ns	ns	ns	ns
2 harvests					
N rate linear		ns	[a]	ns	ns
N rate quad		ns	ns	[a]	ns
3 harvests					
N rate linear		ns	ns	ns	ns
N rate quad		ns	[a]	[a]	ns

SED—standard error of the difference between two equally replicated means.
2-sp N, 2 harv—2 harvest system, N applied in April and after first harvest.
3-sp N, 3 harv—3 harvest system, N applied in April and after each of the first two harvests.
[a]Significant at the 0.05 probability level.
ns—not significant at the 0.05 porbability level.

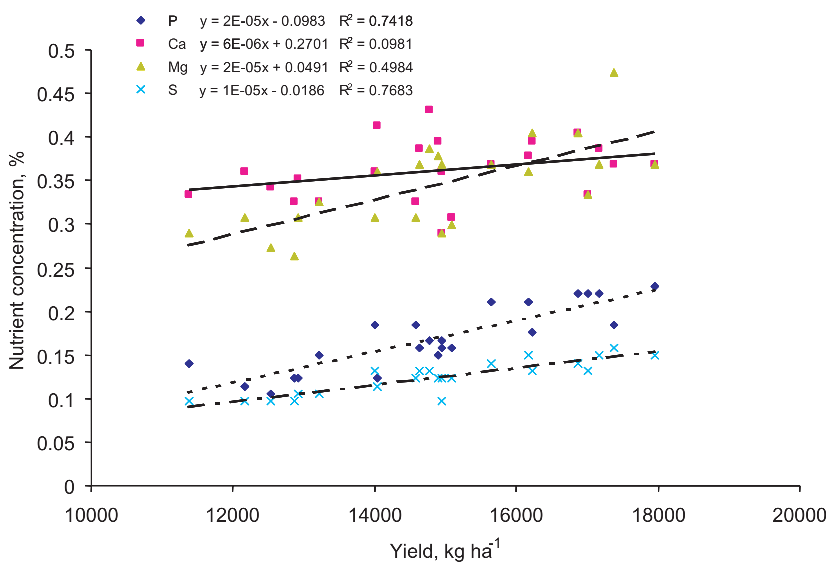

Figure 2. Ca, Mg, P, and S concentrations with increasing dry biomass yields, Chickasha and Perkins. *(View this art in color at www.dekker.com.)*

switchgrass. Similarly, overall P, Mg, and S forage concentrations increased with increasing yield (Fig. 2).

Average dry biomass yields for one, two, and three harvests with 0 and 448 kg N ha^{-1} applied are represented in Figs. 3 and 4 for Chickasha and Perkins respectively. As was expected, yield levels declined with time at Chickasha (Fig. 3). However, this same trend was not observed at Perkins (Fig. 4). It should be noted that even with changes in dry matter yield, nutrient uptake values remained constant. This is a concern especially with increased forage N, as increased N uptake will increase biomass production costs. Practical production recommendations from this work suggest that N be applied once at the beginning of the growing season, and that N rates remain constant over the life of the stand.

Since the goal of this research was to determine maximum recommended N rates for high production, switchgrass data were averaged over years and locations to better estimate optimum N rates and harvest practices. The highest annual yield was consistently achieved with 448 kg N ha^{-1} applied all in April and three harvests during the season averaging 18.0 Mg ha^{-1} dry matter production. This treatment also maximized N, K, P, and S uptake. However, applying 0 N and harvesting three times produced almost as much total biomass

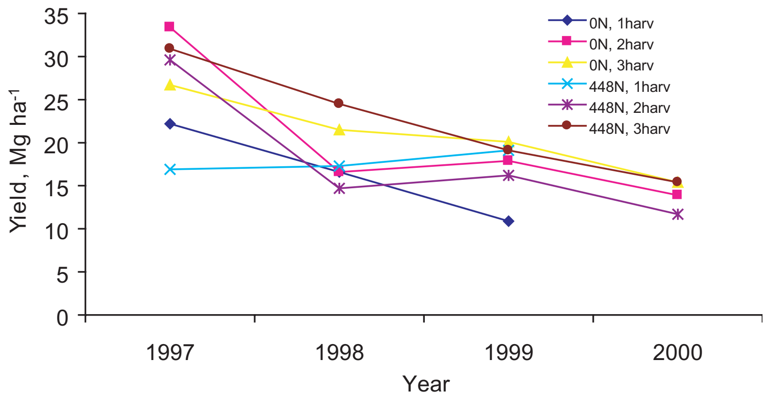

Figure 3. Average yearly dry matter yields over time as influenced by N rate and harvest frequency, Chickasha, OK, 1997–2000. *(View this art in color at www.dekker.com.)*

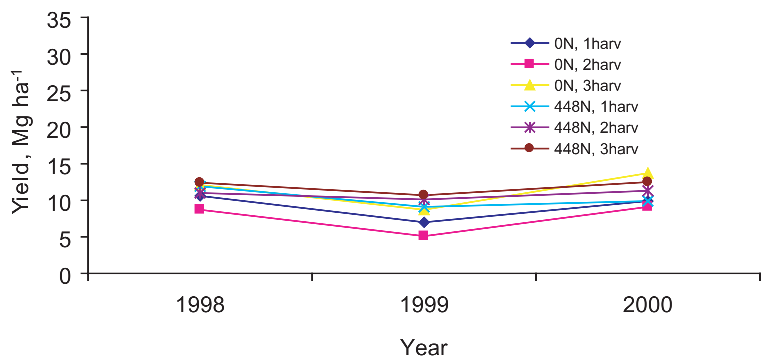

Figure 4. Average yearly dry matter yields over time as influenced by N rate and harvest frequency, Perkins, OK, 1998–2000. *(View this art in color at www.dekker.com.)*

(16.9 $Mg\,ha^{-1}$). This limited response to N is possibly explained by the evolution of switchgrass under low N conditions. The highest level of Ca uptake was observed in plants receiving 224 $kg\,N\,ha^{-1}$ split half in April and half after first harvest and harvested twice. Magnesium uptake was highest where 224 $kg\,N\,ha^{-1}$ was applied in April and with two harvests. Number of harvests was most important in determining yields, with three harvests producing 16.3 $Mg\,ha^{-1}$, two harvests producing 14.7 $Mg\,ha^{-1}$ and one harvest averaging 12.9 $Mg\,ha^{-1}$. Multiple harvests maximized

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yields in every year when compared to one harvest. While multiple harvests have produced more forage in the early years of this study, visual observations indicate a decline in switchgrass stands after 3–4 years of intensive harvest management. Even though there were fewer plants in a given area where multiple harvests were employed, those treatments produced more dry matter than those with higher plant density, but this may change as the stand ages. If density continues to decline, then at some point biomass yield will necessarily decline. It appears that management to maximize productivity in the short-term may shorten the life span of a switchgrass stand.

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