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Biomass Yield and Nutrient Responses of Switchgrass to Phosphorus Application

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Abstract Increasing desire for renewable energy sources has increased research on biomass energy crops in marginal areas with low potential for food and fiber crop production. In this study, experiments were established on low phosphorus (P) soils in southern Oklahoma, USA to determine switchgrass biomass yield, nutrient concentrations, and nutrient removal responses to P and nitrogen (N) fertilizer application. Four P rates (0, 15, 30, and 45 kg Pha⁻¹) and two N fertilizer rates (0 and 135 kg Nha⁻¹) were evaluated at two locations (Ardmore and Waurika) for 3 years. While P fertilization had no effect on yield at Ardmore, application of 45 kg Pha⁻¹ increased yield at Waurika by 17% from 10.5 to 12.3 Mg ha⁻¹. Across P fertilizer rates, N fertilizer application increased yields every year at both locations. In Ardmore, non-N-fertilized switchgrass produced 3.9, 6.7, and 8.8 Mg ha⁻¹, and N-fertilized produced 6.6, 15.7, and 16.6 Mg ha⁻¹ in 2008, 2009, and 2010, respectively. At Waurika, corresponding yields were 7.9, 8.4, and 12.2 Mg ha⁻¹ and 10.0, 12.1, and 15.9 Mg ha⁻¹. Applying 45 kg Pha⁻¹ increased biomass N, and P concentration and N, P, potassium, and magnesium removal at both locations. Increased removal of nutrients with N fertilization was due to both increased biomass and biomass nutrient concentrations. In soils of generally low fertility and low plant available P, application of P fertilizer at 45 kg Pha⁻¹ was beneficial for

increasing biomass yields. Addition of N fertilizer improves stand establishment and biomass production on low P sites.

Keywords Switchgrass biomass · Phosphorus · Nitrogen · Fertilizer · Phosphorus-deficient soil

Introduction

Increasing costs of petroleum-based fuels and national security concerns in the USA have increased research on alternative sources of energy including biomass energy crops. Switchgrass (*Panicum virgatum* L.), a warm-season perennial grass, has potential as a biomass energy crop because of its low soil fertility requirements and adaptation to marginal agro-ecological zones [1]. Early research efforts identified switchgrass varieties and production management strategies to improve production [2], but challenges including P fertilizer requirements for successful feedstock production remain. Expected increases in food demands from an ever-increasing population plus food security concerns may limit production of biomass energy crops to marginal areas not otherwise used for food and fiber crop production. Therefore, it is prudent to determine the lowest rates of fertilizer required by these soils for acceptable biomass yields and quality at minimal costs [2].

Sustaining switchgrass as a source of biomass for energy requires fertilizer management strategies that optimize yield, minimize nutrient removal, and reduce costs associated with fertilizer application [3]. Because switchgrass can grow and thrive successfully in low fertility soil, a tremendous potential exists for its production in the marginal areas of the southern Great Plains. However, there is limited information on its fertilizer requirement including phosphorus (P) rates needed to optimize biomass yields. Previous research in this

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region has generally shown that switchgrass biomass yields respond to nitrogen (N) fertilizer rates of up to 168 kg ha⁻¹, depending on ecotype and location [4–6]. Phosphorus, a plant macronutrient reported to limit plant growth and productivity in 40% of the world's arable soil [7], is a constituent of macromolecular structures like nucleic acids and is critical for synthesis of energy transfer organic compounds such as adenosine triphosphate in plants [8]. Plants growing in P-deficient conditions have reduced leaf expansion and leaf area [9], leaf number [10], and photosynthetic efficiency [11]. In a bioenergy crop like switchgrass, where high vegetative biomass accumulation is important, P fertilization may be necessary to maximize leaf area and photosynthetic activity. The timing of biomass harvests may also influence P requirements. In perennial grasses, delaying biomass harvest to post-senescence period allows mineral elements to be remobilized from aboveground to belowground tissues [12] and reduces biomass nutrient concentrations [6, 13–15]. This recycling of nutrients, in turn, may reduce fertilizer requirements and costs. It is unclear whether further increases in biomass yields may be achieved with P application on N-fertilized and non-N-fertilized switchgrass in a low P soil. In a P-deficient soil in the southern Great Plains, positive responses to P fertilizer application have been reported in traditional forage and grain crops [16–18].

Despite presence of data showing P fertilizer response of switchgrass grown for forage in low P soils [19–22] and in greenhouse studies [23], there is a paucity of information on the effects of P on biomass yields of switchgrass harvested after frost for bioenergy. Therefore, experiments were conducted from 2008 to 2010 at two locations in southern Oklahoma to evaluate how P fertilizer rates affect switchgrass on P-deficient soils in the Great Plains. The objectives were to evaluate effects of P application rate on biomass yields, nutrient concentrations, and nutrient removal rates of N-fertilized and non-N-fertilized switchgrass. It was hypothesized that: (1) P and N fertilization would increase biomass yield, (2) mineral element concentrations of post-frost biomass would be comparable between fertilized and unfertilized switchgrass, and (3) fertilized switchgrass would remove comparable amounts of mineral elements as unfertilized switchgrass in post-frost harvested material.

Materials and Methods

Research was established in spring 2008 on 1-year-old stands of “Alamo” switchgrass at the Samuel Roberts Noble Foundation Headquarters Farm located at Ardmore, OK (34°10' N, 97°8' W) and the Howard Cattle Company near Waurika, OK (34°10' N, 97°47' W). Soil was a Normangee loam (fine, smectitic, thermic Udertic Haplustalfs) at Ardmore and a Zaneis–Pawhuska complex (fine-loamy,

silicious, active, thermic udic Argiustolls) at Waurika. The soil chemical characteristics and plot management activities are given in Table 1. Prior to establishing the switchgrass stand, the field at Waurika was used for production of wheat harvested for hay, while that at Ardmore was also for production of hay from a mixed stand of bermudagrass (*Cynodon dactylon* L.) and crabgrass (*Digitaria* sp.). The experiments were randomized complete block designs with a split-plot arrangement of N rates as whole plots, P rates as sub-plots, and four replications. Treatments applied to 2.4 × 6.1-m plots included four P fertilizer rates (0, 15, 30, and 45 kg Pha⁻¹) applied as triple superphosphate (0–46–0) and two N fertilizer rates (0 and 135 kg Nha⁻¹) applied as ammonium nitrate (34–0–0). Both N and P were applied annually in spring from 2008 to 2010.

In 2008, 2009, and 2010, switchgrass was harvested after the first killing frost with either a Carter (Brookston IN) forage harvester (2009–2010) or a Hege (Colwich, KS) forage plot harvester (2008) at a 10-cm height. Field operations including dates for first killing freeze and after-frost biomass harvest at Ardmore and Waurika are given in Table 1. Subsamples of the harvested biomass were collected, dried at 60°C for dry matter determination, and ground to pass a <1-mm screen using a Wiley Mill (Thomas Scientific, Swedesboro, NJ) for nutrient analysis. Nitrogen, P, K, calcium (Ca), and magnesium (Mg) concentrations were estimated with near infrared spectroscopy (NIRS) analysis [24] using equations developed by the NIRS Forage and Feed Testing Consortium (Hillsboro, WI). The N concentration mean, standard error of validation, and *r*² for the equation used were: 2.0 gkg⁻¹, 0.2 gkg⁻¹, and 0.98, respectively. The P concentration mean, standard error of validation, and *r*² for the equation used were: 1.9 gkg⁻¹, 0.4 gkg⁻¹, and 0.73, respectively. The K concentration mean, standard error of validation, and *r*² for the equation used were: 16 gkg⁻¹, 2.8 gkg⁻¹, and 0.85, respectively. The Ca concentration mean, standard error of validation, and *r*² for the equation used were: 4.9 gkg⁻¹, 0.9 gkg⁻¹, and 0.84, respectively. The Mg concentration mean, standard error of validation, and *r*² for the equation used were: 2.6 gkg⁻¹, 0.5 gkg⁻¹, and 0.91, respectively. These equations were then used to predict N, P, K, Ca, and Mg concentrations for all samples. Nutrient removal rates were determined by multiplying nutrient concentrations by dry biomass yields.

Analysis of data was conducted using PROC MIXED [25] to determine main effects and interactions of location, N fertilizer rate, P fertilizer rate, and year on biomass yield, nutrient concentrations, and nutrient removal rates. Location, N fertilizer rate, P fertilizer rate, and year were considered fixed effects, and replications were considered random effects. When location interaction was significant, the effects of P rate, N rate, and year were analyzed for each location. Block by N rate error term was used to test for N rate effect, and block by P rate and block by N rate by P rate

Table 1 Soil characteristics (0–15 cm depth) and timing of field operations and management activities for phosphorus and nitrogen fertilizer study from 2008 to 2010 at Ardmore and Waurika, Oklahoma, USA

Character	Unit	Location	
		Ardmore	Waurika
Soil characteristics			
pH		6.1	5.9
Organic matter	(%)	2.2	1.6
NO ₃ -N	(mg kg ⁻¹)	0.5	7.2
P	(mg kg ⁻¹)	3.1	3.4
K	(mg kg ⁻¹)	133	121
Ca	(mg kg ⁻¹)	1865	567
Mg	(mg kg ⁻¹)	546	157
Na	(mg kg ⁻¹)	62	42
Field operations, conditions, and management			
Year			
2008	Fertilizer application	21 April	17 April
	First day of freezing temperature	15 November	16 November
	Biomass harvest	12 December	18 December
2009	Fertilizer application	3 March	11 March
	First day of freezing temperature	18 November	18 November
	Biomass harvest	7 December	5 January 2010
2010	Fertilizer application	26 March	29 April
	First day of freezing temperature	25 November	14 November
	Biomass harvest	15 January	28 December

error term were used to test for P rate effect and N rate by P rate interaction. Orthogonal contrast analysis of linear and quadratic effects of P fertilizer was done for measured parameters. The statistical models applied the autoregressive (AR1) spatial power covariance structure to account for temporal autocorrelation in data collected across years. Statistical significance was determined at $P=0.05$.

Results

Weather Conditions and Overall Trends

Precipitation varied considerably from year to year at Ardmore but was less variable at Waurika (Table 2). At Ardmore, the long-term 30-year average precipitation was 951 mm, and the annual precipitation received was 641, 1132, and 806 mm in 2008, 2009, and 2010, respectively. At Waurika, the 30-year average precipitation was 810 mm, and the annual precipitation was 875, 922, and 751 mm, respectively (Table 2). Ardmore received 33% and 15% below normal precipitation in 2008 and 2010, respectively, but 19% above normal precipitation in 2009. At Waurika, precipitation was 8% above normal in 2008, and 14% above normal in 2009, but 7% below normal in 2010.

Effects of Phosphorus Rate on Biomass, Nutrient Concentration, and Removal

Year by location and location by P fertilizer rate interactions were significant; therefore, data were analyzed by location. Year by P fertilizer and N fertilizer by P fertilizer interactions were not significant; therefore, P fertilizer means were pooled across years and N fertilizer rates for each location.

Ardmore

At the Ardmore location, P fertilizer had no effect on switchgrass biomass yield; however, it tended to increase N and P tissue concentrations as well as nutrient removal (Table 3). Phosphorus fertilizer had no effect on K, Ca, and Mg concentration of harvested biomass which averaged 3.4, 2.8, and 2.7 gkg⁻¹, respectively. Removal rates of N, P, K, and Mg increased with P application. At 0 kg Pha⁻¹, switchgrass N, P, K, and Mg removal rates were 45.8, 7.7, 28.1, and 24.3 kg ha⁻¹, respectively. These amounts were lower ($P<0.05$) than nutrient removal by switchgrass receiving 45 kg Pha⁻¹ that averaged 66.8, 10.0, 38.2, and 28.9 kg ha⁻¹, respectively.

Waurika

At the Waurika location, biomass yield showed a linear response to P fertilizer application (Table 3). Although P fertilizer

Table 2 Monthly precipitation and temperatures for 2008, 2009, 2010 and the long-term average (1971–2000) at Ardmore and Waurika, Oklahoma, USA

Location	Year	Month												Total/mean
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Precipitation, mm														
Ardmore	2008	3	41	134	69	114	61	36	82	48	35	13	5	641
	2009	15	36	30	157	269	46	113	60	134	195	5	72	1132
	2010	43	68	49	87	88	59	115	30	156	59	46	6	806
	Long term	46	53	74	103	134	100	69	67	92	94	64	56	951
Waurika	2008	1	20	115	103	58	59	102	299	48	47	12	11	875
	2009	10	20	20	203	97	82	78	48	118	166	11	69	922
	2010	50	58	25	108	86	145	81	6	104	67	8	13	751
	Long term	41	44	75	86	91	100	57	75	66	89	43	42	810
Temperature, °C														
Ardmore	2008	5.0	7.7	12.3	16.3	21.5	26.5	28.6	26.7	21.7	17.2	11.8	5.9	16.8
	2009	5.1	10.6	13.2	16.7	20.0	27.0	27.9	26.8	21.8	14.3	13.4	2.9	16.6
	2010	3.7	3.5	11.0	17.7	21.7	27.8	27.8	29.6	24.2	17.7	12.1	6.3	16.9
	Long term	4.8	7.1	11.6	16.5	20.8	25.0	27.9	27.6	23.3	18.6	11.9	6.5	16.8
Waurika	2008	5.0	7.4	12.9	16.5	22.1	27.8	28.6	26.9	21.8	17.0	11.5	5.6	16.9
	2009	4.4	10.6	13.8	17.2	20.1	26.9	28.2	27.8	22.2	14.4	12.5	2.5	16.7
	2010	3.6	3.7	11.0	17.4	21.5	27.8	27.2	30.2	24.6	17.5	11.8	6.2	16.9
	Long term	5.3	8.0	12.1	17.0	21.8	26.2	28.9	28.6	23.7	17.6	11.6	5.9	17.2

rates of up to 30 kg ha⁻¹ produced similar biomass to the control ($P=0.05$), application of 45 kg Pha⁻¹ produced 17% higher yield (12.3 Mg ha⁻¹). There was a linear increase in N and P concentration with P fertilizer application (Table 3). Biomass K and Mg concentration increased with the first increment of P fertilizer (15 kg Pha⁻¹), but no further increase occurred with higher P fertilizer rates.

Switchgrass receiving no P fertilizer had N, P, K, and Mg concentrations of 6.4, 0.85, 2.4, and 2.9 gkg⁻¹ (Table 3). Applying 15 kg Pha⁻¹ increased the concentrations by between 6% and 21% to 7.3, 0.90, 2.9, and 3.1 gkg⁻¹, respectively (Table 3). At the Waurika location, there was a linear increase in N, P, K, Ca, and Mg removal rates with P fertilizer application (Table 3). Removal rates for N, P, K, Ca, and Mg by non-P-fertilized switchgrass were 73.1, 9.5, 23.4, 31.1, and 32.4 kg ha⁻¹, respectively. Application of P fertilizer increased nutrient removal by 25% to 47% to 107.2, 12.4, 32.6, 40.2, and 40.4 kg ha⁻¹, respectively (Table 3). The removal rates for P and Mg at P fertilizer rates greater than 15 kg ha⁻¹ were similar ($P=0.05$). Switchgrass receiving some level of P fertilizer had higher removal rates of N and K compared to the control.

Effects of Nitrogen Rate on Biomass, Nutrient Concentration, and Removal

Year by location and location by N fertilizer rate interactions were significant; therefore, data were analyzed by location.

Year by N fertilizer rate interactions were significant, while N fertilizer by P fertilizer was not significant; therefore, N fertilizer means are reported by year pooled across P fertilizer rates for each location.

Ardmore

At the Ardmore location, switchgrass biomass yields ranged from 3.9 to 16.6 Mg ha⁻¹ (Table 4). Nitrogen fertilizer increased switchgrass yield each year; however, due to 33% below normal rainfall in 2008, the magnitude of difference was not the same, which caused the interaction by year. Non-N-fertilized switchgrass produced 3.9 Mg ha⁻¹ in 2008 and yields increased to 6.7 and 8.8 Mg ha⁻¹ in 2009 and 2010, respectively (Table 4). When compared to the control, switchgrass fertilized with 135 kg Nha⁻¹ increased yield to 6.6 Mg ha⁻¹ (69% increase), 15.7 Mg ha⁻¹ (134% increase), and 16.6 Mg ha⁻¹ (89% increase) in 2008, 2009, and 2010, respectively, compared to non-N-fertilized switchgrass.

The year by N fertilizer interaction affected biomass nutrient concentrations and removal rates (Table 4). In 2008, N fertilization did not affect N, P, and Mg concentrations which averaged 2.5, 0.58, and 3.0 gkg⁻¹, respectively. Nitrogen fertilization increased N, P, and Mg concentrations from 4.1 to 10.1, 0.76 to 1.26, and 2.7 to 3.6 gkg⁻¹ in 2009 and from 3.6 to 5.7, 0.78 to 0.92, and 2.0

Table 3 The effect of P fertilizer on biomass yield (dry matter basis), biomass concentration, and removal rates of N, P, K, Ca and Mg in switchgrass harvested after a killing frost averaged across N fertilizer rates and years at Ardmore and Waurika, Oklahoma, USA

P rate, kg Pha ⁻¹	Yield, Mg ha ⁻¹	Nutrient concentration					Nutrient removal				
		N g kg ⁻¹	P	K	Ca	Mg	N kg ha ⁻¹	P	K	Ca	Mg
Ardmore											
0	9.2a	4.3b	0.77b	3.2a	2.8ab	2.7a	45.8b	7.7b	28.1b	23.9a	24.3b
15	9.6a	4.7ab	0.81ab	3.4a	3.1a	2.7a	55.2b	8.9ab	34.1ab	27.2a	27.1b
30	9.6a	4.5ab	0.82ab	3.6a	2.7b	2.7a	55.0b	8.8ab	33.0ab	24.2a	25.8ab
45	10.4a	5.2a	0.86a	3.6a	2.7b	2.7a	66.8a	10.0a	38.2a	27.5a	29.0a
<i>p</i> value											
Linear	0.07	0.02	<0.01	0.14	0.17	0.52	<0.01	<0.01	0.04	0.24	0.02
Quadratic	0.74	0.58	0.91	0.71	0.25	0.76	0.76	0.98	0.90	0.99	0.89
Waurika											
0	10.5b	6.4b	0.85b	2.4b	3.1b	2.9b	73.1c	9.5b	23.4b	31.1c	32.4b
15	10.7b	7.3a	0.90a	2.9a	3.4a	3.1a	84.1b	10.3b	29.6a	34.7b	34.2b
30	10.8b	7.3a	0.90a	2.9a	3.3ab	3.2a	84.7b	10.4b	30.8a	33.9bc	34.4b
45	12.3a	7.8a	0.93a	2.8a	3.3ab	3.2a	107.2a	12.4a	32.6a	40.2a	40.4a
<i>p</i> value											
Linear	0.04	0.05	0.03	0.17	0.31	0.13	<0.01	<0.01	0.06	0.03	0.03
Quadratic	0.29	0.78	0.88	0.13	0.21	0.78	0.46	0.44	0.52	0.62	0.39

At each location, values in a column followed by the same letter were not significantly different (*P*=0.05)

to 2.3 gkg⁻¹ in 2010, respectively. In general, the concentrations of K and Ca in biomass were lowest in 2010 compared to the 2008 and 2009 seasons. In 2008, N and P removal was not affected by N application and averaged 13

and 3 kg ha⁻¹, respectively. Nitrogen and P removal rates for non-N-fertilized switchgrass were 27 and 5 kg ha⁻¹ in 2009 and 31 and 7 kg ha⁻¹ in 2010. Switchgrass fertilized with N had removal rates of 156 kg Nha⁻¹ and 20 kg Pha⁻¹ in 2009

Table 4 The effect of N fertilizer on biomass yield (dry matter basis), biomass concentration, and removal rates of N, P, K, Ca, and Mg in switchgrass harvested after a killing frost during the 2008, 2009, and 2010 season at Ardmore and Waurika, Oklahoma, USA

Year	N rate, kg Nha ⁻¹	Yield, Mg ha ⁻¹	Nutrient concentration					Nutrient removal				
			N g kg ⁻¹	P	K	Ca	Mg	N kg ha ⁻¹	P	K	Ca	Mg
Ardmore												
2008	0	3.9d	2.4d	0.61d	3.9b	3.2b	3.0b	9.3e	2.3e	15.1c	12.8c	11.5d
2009	0	6.7c	4.1c	0.76c	2.9c	3.8a	2.7c	27.0cd	5.1d	19.7c	25.3b	17.8c
2010	0	8.8b	3.6c	0.78c	1.5d	1.6c	2.0e	30.7c	6.9c	13.3c	12.4c	16.7c
2008	135	6.6c	2.6d	0.56d	5.0aa	3.8a	3.0b	16.4de	3.7de	33.7b	21.0b	19.5c
2009	135	15.7a	10.1a	1.26a	4.8ab	3.2b	3.6a	156.4a	19.7a	77.2a	58.9a	56.0a
2010	135	16.6a	5.7b	0.92b	2.5cd	1.4c	2.3d	94.6b	15.5b	41.0b	23.6b	37.7b
Waurika												
2008	0	7.9d	6.4c	0.77c	3.9a	4.0a	3.5a	66.8c	6.8d	30.6bc	35.0b	30.5c
2009	0	8.4d	6.2c	0.81c	2.4b	3.7b	3.0b	54.9d	6.9d	20.8d	30.5c	25.7d
2010	0	12.2b	5.2d	0.91b	1.2c	1.8c	2.4d	69.0bc	11.5c	13.1e	22.7d	31.6c
2008	135	10.0c	10.5a	0.72d	4.0a	4.2a	3.6a	80.7b	7.7d	36.9b	43.8a	37.6b
2009	135	12.1b	8.1b	1.10a	3.2b	4.0ab	3.6a	123.9a	13.7b	44.8a	46.9a	43.6a
2010	135	15.9a	8.5b	1.10a	1.7c	1.9c	2.7c	128.0a	17.2a	22.3cd	30.9bc	43.1a

At each location, values in a column followed by the same letter are not significantly different (*P*=0.05)

and 95 kg N ha⁻¹ and 16 kg P ha⁻¹ in 2010. Removal rates for K, Ca, and Mg in non-N-fertilized switchgrass were 13–20, 12–25, and 12–18 kg ha⁻¹ year⁻¹, respectively (Table 4). Application of N fertilizer increased K, Ca, and Mg removal in all production years. In 2009, N-fertilized switchgrass removal rates for K, Ca, and Mg were highest averaging 77.2, 58.9, and 56 kg ha⁻¹, respectively. Although K, Ca, and Mg removal rates by N-fertilized switchgrass in 2008 and 2010 were approximately 50% lower than in 2009, they averaged 110% higher than removal rates by non-N-fertilized switchgrass during the same years (Table 4).

Waurika

At the Waurika location, switchgrass biomass yields ranged from 7.9 to 15.9 Mg ha⁻¹ (Table 4). Switchgrass receiving no N fertilizer produced 7.9, 8.4, and 12.2 Mg ha⁻¹ in 2008, 2009, and 2010, respectively. Application of 135 kg N ha⁻¹ increased yield by between 26% and 44% to reach 10.0, 12.1, 15.9 Mg ha⁻¹ in 2008, 2009, and 2010, respectively.

At the Waurika location, N fertilizer application increased biomass N concentration in all years, P and Mg concentration in 2009 and 2010, but had no effect on K and Ca concentration (Table 4). In 2009 and 2010, N, P, and Mg concentrations for non-N-fertilized switchgrass were 6.2 and 5.2 g kg⁻¹, 0.81 and 0.91 g kg⁻¹, and 3.0 and 2.4 g kg⁻¹, respectively. In 2009 and 2010, N, P, and Mg concentration increased with N fertilizer application by 31 and 63%, 36 and 21%, and 20 and 13%, respectively. Concentration of K and Ca varied with years, and K (4.0 g kg⁻¹) and Ca (4.1 g kg⁻¹) in 2008 were the greatest and K (1.5 g kg⁻¹) and Ca (1.9 g kg⁻¹) in 2010 the least. In all production years, N application at Waurika increased nutrient removal rates except P and K in 2008 (Table 4). In 2008, N fertilizer application increased N removal by 21% from 66.8 to 80.7 kg ha⁻¹. Nitrogen removal with N fertilizer application increased by more than 85% from 54.9 and 69.0 to 123.9 and 128 kg ha⁻¹ in 2009 and 2010, respectively (Table 4). Application of N fertilizer increased P removal from 6.9 to 13.7 and 11.5 to 17.2 kg ha⁻¹ in 2009 and 2010, respectively (Table 4). Similarly, N application increased K removal rate by over 100% from 20.8 to 44.8 and 13.1 to 28.3 kg ha⁻¹ in 2009 and 2010, respectively. Removal rates of Ca and Mg varied by year and increased with N application by between 25–54% and 23–70% (Table 4).

Discussion

Differences in dry matter yield between years for a given location were most likely a result of differences in the amount of rainfall received during March to September. During period of vegetative growth (March–September), Ardmore received 40% more precipitation in 2009 than in

2008. Also in July of 2008, in addition to receiving threefold lower precipitation than in 2009, Ardmore mean temperature was about 1°C hotter (Table 1). This difference in precipitation may explain the 72% increase in biomass for control plot and the 134% increase in biomass with N fertilizer application in 2009 compared to 2008 production year. Greater responses to N fertilizer under conditions of high soil moisture or precipitation amounts have been reported previously [26–28]. Unlike Ardmore, low percentage biomass increase in Waurika from 2008 (year 1) to 2009 (year 2) can be attributed to similarity in amount of precipitation between the 2 years. Although not determined, increased yield from year to year for non-N-fertilized switchgrass at both locations could also be a result of improving switchgrass stand.

The additional biomass of 1.2 Mg ha⁻¹ (13% increase) at Ardmore and the 1.8 Mg ha⁻¹ (17% increase) at Waurika obtained with 45 kg P ha⁻¹ was comparable to 20% increase in switchgrass forage biomass observed with application of 50 kg P ha⁻¹ on a low P soil in Virginia [22]. Similar increases in switchgrass forage yield in response to P fertilization have been reported elsewhere [19–21] and also in greenhouse studies [23]. A 22% increase in forage yield in response to 90 kg P ha⁻¹ was reported for four warm-season grasses: bermudagrass (*C. dactylon* L.), weeping lovegrass [*Eragrostis curvula* (Schreb.) Nees], “Plains” bluestem (*Bothriochloa ischaemum* (L.) Keng var. *ischaemum*), and native ranges that included switchgrass in Oklahoma [29]. Unlike a previous study where no yield response to 39 kg P ha⁻¹ was observed for switchgrass in Texas [5], the increased yield obtained with 45 kg P ha⁻¹ in this study may have resulted from better stand development, increased soil plant available P, and better P scavenging by the roots. The low P response may be due to inherent ability of switchgrass to efficiently use P or extract fixed P in the soil. It is reported that switchgrass origin in low fertility soils has allowed it to develop adaptive and tolerance traits to low plant available P soils [30]. Switchgrass forms a symbiotic association with mycorrhizae fungi that improves P scavenging while its deep rooting system allows for access to subsoil P sources [31]. In fact, it is reported that switchgrass with mycorrhizal association had a 30-fold increase in P uptake compared to switchgrass without the fungal symbiont [23]. Though not determined, traits that mitigate P deficiency such as mycorrhizal associations release by roots of carboxylic acids and phosphatases may be at play in the switchgrass under low P soils.

It is possible that high N and P concentration observed with fertilizer application in after-frost material may have also occurred during the growing season. Increased concentration of N, P, and other macronutrients during vegetative growth could have led to better root proliferation, increased root/soil ratio, better root/soil contact, and increased nutrient acquisition. Prolific shoot growth creates nutrient sinks in new tissue, increases nutrient demand and nutrient gradients, and

facilitates improved uptake of all nutrients and their subsequent concentration in the shoots. The result may have been increased plant growth and nutrient accumulation in the tissue which was reflected in increased nutrient removal in harvested biomass.

While N, P, Ca, and Mg removal followed the biomass trend, K removal did not. Potassium removal may not have reflected biomass yields because apart from translocation of this nutrient to underground structures as the plant senescence during fall, K may be leached out of senescing material [3, 31]. In this study, similar losses may have occurred in 2009 and 2010 due to significantly high rainfall in the months of September and October when senescence starts. Because biomass harvest occurred more than 3 weeks after killing frost in all years (Table 1), it would be expected that sufficient nutrient remobilization occurred each time. Therefore, differences in amount of N and P removal among years were likely a result of differences in dry matter yield and biomass N and P concentration at harvest time. At the Ardmore location, high nutrient removal with N fertilization was mainly due to increased biomass, while at Waurika, it was mainly due to increased tissue nutrient concentration with N fertilization.

Conclusions

In soils with low plant available P, application of 45 kg P ha⁻¹ increases biomass yield by up to 17%. Application of N fertilizer increased biomass in these low P soils by an average of more than 45%. Except for K, Ca, and Mg at Ardmore, nutrient concentrations increased with the first increment of P fertilizer for all elements. For all elements except K, the amount of nutrient removed increased with increasing biomass yield. Therefore, in soils with low plant available P, phosphorus fertilizer should be applied to increase switchgrass yield, replace P removed in harvested biomass, and sustain soil productivity.

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