Managing Nitrogen and Phosphorus Nutrients for Switchgrass Produced for Bioenergy Feedstock in Phosphorus-Deficient Soil

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Abstract

There is limited information available explaining the agronomic and economic relationships between yield and nitrogen and phosphorus applications to growing switchgrass produced in phosphorus-deficient soils. The objective of this study was to determine the effects of nitrogen and phosphorus fertilizers on feedstock yield and measures of expected total cost, gross revenue, net return, and breakeven price of feedstock produced in phosphorus-deficient soils in the southern Great Plains. Data were collected from a three-year, two-location agronomic field study conducted in south-central Oklahoma. Two discrete nitrogen treatments (0 and 134 kg ha^{-1}) and four discrete phosphorus treatments (0, 30, 60 and 90 kg ha^{-1}) were randomly assigned to small plots arranged in a randomized complete block designed (RCBD) study. Random effects mixed ANOVA models were used to estimate the effects of nitrogen, phosphorus and nitrogen by phosphorus interactions on feedstock yield and the economic variables specified. Results showed that, on average over site-years, switchgrass yield increases from 10.5 to 12.3 Mg ha^{-1} with the highest (101-kg ha^{-1}) P_2O_5 treatment; however, we found no statistical difference in net profitability between phosphorus treatments. Yield and net return did respond significantly to 135 kg^{-1} of N ha^{-1}. Our results suggest that phosphorus-deficient soils do not seem to have the same impact on switchgrass yield and profitability as they do for the yields and profitability of other crops traditionally grown in this region.

Key words: bioenergy feedstock, economics, phosphorus-deficient soils, nitrogen, switchgrass

INTRODUCTION

Native to the southern Great Plains, switchgrass (*Panicum virgatum L.*) has been classified by agricultural scientists and public decision makers as a leading source of cellulosic feedstock for the large-scale production of bioenergy fuels, such as ethanol. Once switchgrass is established, proper management of nutrients is essential to maintain and sustain a high quality, high yielding stand. At present, much of the published economic research regarding nutrient management for switchgrass has focused primarily on nitrogen fertilizer as the primary limiting nutrient(Vogel et al., 2002; Mulkey, Owens, and Lee, 2006; Lemus et al., 2008; Haque et al., 2009; Aravindhakshan et al., 2011; Stout, Jung, and Shaffer, 1988; and Ranney and Mann, 1994). For these studies, soil phosphorus levels were determined to be adequate, not yield limiting. However, some literature provides signals that a significant portion of the soils in the south-central Great Plains are phosphorus-deficient, and responsible for limiting the growth of crops commonly produced in the region (Mays et al. 1980; Zhang 2008).

Phosphorus is an essential nutrient for all plant growth, development, and reproduction. A number of studies report that crops common to the southern Great Plains require application of both nitrogen and phosphorus nutrients (Bauder, 1996; Elstein, 2004; Butler et al., 2006). Economic analyses of several long-term agronomic field experiments conducted by the Agricultural Research Service (ARS) on crops (wheat, barley, corn and other crops) in the Great Plains revealed that farmers can achieve greater economic net returns if the correct amount of phosphorus is applied to eliminate phosphorus deficiency (Elstein, 2004). An economic study conducted in Montana (Bauder, 1996) evaluated the economic benefits and cost for applying fertilizer on eleven different crops. They found poor yield responses (and hence economic losses) when nitrogen fertilizer was applied without P relative to the responses (and significantly greater economic net returns) of the same crops when P was added with N. An agronomic study of rye-grass in Texas reported that in the first of a two year study, forage yield responded by more than 34% to a 45 kg ha^{-1} application of P_2O_5 compared to the zero level control treatment, and by 37% in the second year with same level of P_2O_5 application (Butler et al., 2006).

Published research has also been done that evaluated switchgrass yield response to nitrogen and phosphorus fertilization, but reported mixed agronomic results regarding yield response to phosphorus fertilization. For example, Muir et al. (2001) estimated a switchgrass yield response to nitrogen and phosphorus function using data collected in north-central and south Texas. They found that biomass yield grown on low phosphorus (phosphorus deficient) soils did not respond to phosphorus. Similar results were found in Iowa where a study was initiated to evaluate the effects of fertilization on herbage dry matter yield on three-warm season grasses including switchgrass (Hall, George and Riedl, 1982). They found no response of P when applied to switchgrass in low-P soils in Iowa. Conversely, other studies did observe positive responses of P fertilization on yield (Taylor and Allinson, 1982; Rehm, 1984). Taylor and Allinson (1982) found that phosphorus is a limiting factor for switchgrass on soils low in P and nitrogen and did not significantly increase yields above the control treatment in the first harvest without P application. They recommended the application of nitrogen in conjunction with phosphorus in order to obtain the maximum response from applied phosphorus. In addition, research done in Nebraska by Rehm (1984) found highly significant linear relationship between switchgrass forage yield and phosphorus and nitrogen. However, most of these studies did not evaluate the biomass feedstock response from phosphorus applications; instead they focused on the forage potential for livestock activity. Furthermore, none of these studies considered the benefits and costs associated with phosphorus application.

Despite its potential for use as a cellulosic feedstock for producing bioenergy in the southern Great Plains, little information is available that reports results from agronomic and economic relationships between switchgrass biomass yield and nitrogen and phosphorus fertilizer application in phosphorus deficient soils. The objectives of this study was to determine the effects of nitrogen and phosphorus fertilizers on yield, breakeven feedstock price, and economic net return to land, management, and overhead, and (2) to determine the best nutrient management practices for producing switchgrass in the phosphorus-deficient soil in the Southern Great Plains. Information gleaned from this research will be valuable to farmers that may be interested in growing switchgrass for bioenergy feedstock, and to production scientists and extension educators working towards developing best management practices for economical applications of nutrients for switchgrass in the Southern Great Plains.

THEORETICAL FRAMEWORK

Switchgrass has been purported as a “low input” perennial grass species that can be produced with little or no additions of fertilizer while maintaining high productivity [Tilman, Hill, and Lehman, 2006]. However, if substantial quantities of biomass are removed each year prior to plant senescence, then additional nutrient application has been show necessary (Guretzky et al., 2010). Switchgrass has the potential to open up new markets for producers since it can grow in a variety of soils including marginal agricultural lands that may not be suitable for other crops. Despite this potential, the market for switchgrass as an energy feedstock does not exist in the southern Great Plains, and so producers are not currently growing switchgrass as a biorefinery feedstock. A rational farmer would be willing to adopt the switchgrass feedstock enterprise onto his farm only if the expected net profit by adopting switchgrass is greater than their current level of profit from crops they currently produce. As a result, an expected profit maximization framework was identified and used as producer’s decision making tool.

The producer’s objective is to choose the levels of N and P that will yield him the greatest net return to his labor, management and overhead. This objective function is represented mathematically as:

$$\max_{N,P} E(NR) = \max\left\{E\left(\rho Y(N,P)\right) - r_N N - r_P P - r_h H(Y(N,P)) - FC\right\},$$

Subject to:

$Y \geq Y(N,P)$;

$N \in (0, 135)$;

$P \in (0, 34, 67, 101)$;

$r_N, r_P, r_h \geq 0;$

$$N, P \geq 0. \qquad (1)$$

where $E(NR)$ is the expected net return (\$ ha^{-1}) to management and overhead from growing and marketing switchgrass feedstock; p is the expected price of feedstock (\$ Mg^{-1}); N represent the two discrete nitrogen treatment levels evaluated (0, 135 kg ha^{-1}); P represent the four discrete phosphorus treatments levels evaluated in the study (0, 34, 67, 101 kg ha^{-1}); $r_N, r_P, and\ r_h$ represent the price of nitrogen, price of phosphorus, custom rates for raking, cutting, bailing and staging switchgrass feedstock. H represents the quantity of baling feedstock in the field and is a function of feedstock yield; and FC represents fixed costs.

MATERIALS AND METHODS

Agronomic

Data were collected from field experiments conducted at The Samuel Roberts Noble Foundation's Headquarters Farms at Ardmore (34° 10' N / 97° 8'W), OK and at the Howard Ranch Farm at Waurika (34 ° 10' N / 97° 47'W), OK. The experiment started in 2007 in phosphorus deficient soil to evaluate the effects of phosphorus and nitrogen application on switchgrass yield. The data set used is this study was based on 3 production years from 2008 to 2010. The soil at Ardmore is a Normangee loam (fine, smectitic, thermic udertic Haplustalfs) and the soil at Waurika is a Zaneis-Pawhuska complex (fine-loamy, silicious, active, thermic udic Argiustolls). Samples were taken to a 0-15 cm depth soil at Waurika in April of 2007, pH was 5.9, OM was 1.6%, N was 19 kg ha^{-1}, P was 19 kg ha^{-1} and K was 307 kg ha^{-1}. And, at Ardmore, soil at 0-15 depth showed a pH of 6.1, OM 2.3%, 1 kg N ha^{-1}, 7 kg P ha^{-1}, and 327 kg K ha^{-1}.

Alamo switchgrass was planted at 5.6 kg ha^{-1}seed on 17 May 2007 on land that previously had been used for forage wheat (*Triticumaestivum* L.) at Waurika and at Ardmore on 15 May, 2007 on land that was under fallow with mixture of grasses dominated by bermudagrass from previous summer. Switchgrass was planted at both locations on a clean-tilled prepared seed bed using a SS-series Brillion seeder (Brillion farm equipment, Brillion, WI, USA). No herbicide was applied to the Waurika location before switchgrass was established. In Ardmore, a single application (2.34 L h^{-1}) of Glyphosate [N-(phosphonomethyl) glycine] was applied across the plots to suppress all grassy weeds before the establishment of switchgrass. At Waurika, a single application (3.51 Lh^{-1}) of 2,4-D Amine (2,4-dichlorophenoxyacetic acid, dimethyl amine) and at Ardmore, a single application (0.39 Lh^{-1}) of Journey herbicide was applied on 30 July and 27 July, 2007, respectively to control broadleaved weeds of all plots.

A randomized complete block design with a split-plot arrangement of treatments and four replications was used. Four rates of P (0, 34, 67, and 101 kg ha^{-1}) and two rates of N (0, 135 kg ha^{-1}) were broadcast to 2.4 x 6.1 m plots in the springs of 2008, 2009, and 2010 in both locations. Potassium was broadcast in both locations at a rate of 135 kg ha^{-1} yr^{-1} after establishment year. Phosphorus, N, and K were applied in the form of P_2O_5 (0-46-0), urea (46-0-0), and K_2O (0-0-60), respectively. No fertilizer was applied during the establishment year and the plots were not harvested as recommended for stand longevity (Lawrence et al. 2006). Switchgrass was harvested in 2008, 2009, and 2010 with either a Carter forage harvester or a HEGE forage plot harvester at a 10-cm height at least 30 days after plant senescence (in December or January after a hard freeze). Subsamples of the harvested biomass were collected, dried at 60°C and their dry weights determined. A total of 192 observations were collected from the experiment.

Ardmore received 639, 1131, and 851 mm level of precipitation in 2008, 2009 and 2010, respectively, whereas average precipitation rate over 30 years of time period (1971-2000) is 975 mm for this location. Figure 1 reports precipitation level observed in 2008–2010 and average of 30-yr (1971-2000) at Ardmore, OK and Waurika, OK (Oklahoma Mesonet, 2011). The precipitation rate at Waurika was 875, 921 and 751 mm and the precipitation rate on average over 30 (1971-2000) years of time period at this location is observed at 808 mm. There is year-to-year variability in precipitation at Ardmore, but it was more consistent at Waurika. Average precipitation was slightly above average in 2008 and 2009 but slightly below average in 2010 compared to the precipitation level observed across 30-yr for Waurika. But for Ardmore, average precipitation is slightly below in 2010 but much higher in 2009 and much less in 2008 than the average level observed over 30-yr. Further details of the agronomic field experiments can be found in Kering et al., 2012.

Economic

Standard enterprise budgeting techniques were used to compute expected values for costs, revenues, net returns and breakeven prices for switchgrass feedstock for four different P_2O_5 levels, two levels of N, and eight different combinations of the N x P interactions. The costs of establishment included seed bed preparation, seed and seed planting, herbicide (glyphosate and 2,4-D amine) and herbicide application, and the current land rental rate for the two sites. The cropland rental value budgeted was \$124 ha^{-1} yr^{-1}. A seeding rate of 5.6 kg of PLS ha^{-1} was budgeted, and a switchgrass seed price of \$55.00 $kg^{-1}$of PLS. The estimated establishment cost was \$118 ha^{-1} and \$124 ha^{-1} for Ardmore and Waurika, respectively. The estimated establishment cost of switchgrass was amortized at a nine percent APR over the seven year expected life of the stand.

Annual variable costs for maintenance of the switchgrass stands included cost of fertilizer (N, P_2O_5, and K_2O) and fertilizer application, cost of harvesting (mowing, raking, baling into large squares bales, and staging), and annual operating interest. The prorated establishment costs and land rent were fixed for each year of the study. Prices of \$1.28 kg^{-1} for N (46–0–0), \$1.17 kg^{-1} for P_2O_5 (0–46–0), and \$1.15 kg^{-1} for K_2O (0-0-60) were used in the base model. The cost of baling large square bales is a function of yield, and so it varied with fertilizer treatment level. The budgeted costs of tillage and seedbed preparation, planting, fertilizer and pesticide application, and harvest operations were based on published state average custom rates (Doye and Sahs, 2010).

At present, there are no commercial refineries that purchase switchgrass feedstock from producers in the southern Great Plains, effectively making the market price for feedstock equal to zero. Previous studies (Epplin, 1996; Hallam, Anderson, and Buxton, 2001; Duffy and Nanhou, 2002; Khanna, Dhungana and Clifton-Brown, 2008; Perrin et al., 2008; Mooney et al. 2008) estimated breakeven costs (prices) of feedstock that ranged from \$30.00 to \$107 Mg^{-1}. Based on these findings, gross revenue and net return was calculated and compared for feedstock prices of \$83, \$110, and \$165 Mg^{-1}. Furthermore, sensitivity analysis was conducted to determine how robust the economic results were to alternative (low, medium and high) prices of N and P_2O_5.

Statistical Methods

Data were plotted in scatter diagrams that revealed a linear relationship existed between switchgrass feedstock yield and levels P_2O_5 and N treatments (Figure 2). Random effects mixed ANOVA models were used to estimate the effects of N and P_2O_5on feedstock yield, revenue, cost, net return and breakeven price using the Mixed Procedures in SAS (Littell et al., 1996; SAS

Institute, 2008). Nitrogen, P_2O_5 and N x P_2O_5 interactions were modeled as fixed effects while site-year (Biermacher et al., 2006; Tembo, Brorsen, and Epplin, 2008) was treated as random (tested using Likelihood ratio test). Fisher's protected F-tests were used to determine differences between treatments for all agronomic and economic models. Least significant difference (LSD) tests were used to scrutinize treatment means ($\propto = 0.05$) in order to identify the most economical levels of nitrogen and P_2O_5 to apply to switchgrass in phosphorus-deficient soils.

The equation used to estimate the effects of N, P_2O_5, and N x P_2O_5 interactions on yield, costs, revenue, net return and breakeven price variables is represented mathematically as:

$$Y_{it} = \beta_0 + \sum_{\mathrm{j}=1}^{3} \beta_{1\mathrm{j}} P_{itj} + \beta_2 N_{it} + \sum_{\mathrm{j}=1}^{3} \beta_{3\mathrm{j}} P_{itj}\, N_{it} + v_t + \varepsilon_{it}, \tag{2}$$

where Y_{it} represents agronomic and economic variables (i.e., feedstock yield (Mg ha^{-1}), cost (\$ ha^{-1}), revenue (\$ ha^{-1}), net return (\$ ha^{-1}) and breakeven price (\$/Mg^{-1}) on plot *i* in site-year *t*; β_0 is the yield intercept; β_1 is the slope parameter for the *j*th discrete level of P_2O_5 on plot *i* in site-year *t*; $\beta_2$is the slope parameter for the two discrete levels of N on plot *i* in site-year *t*; β_3 is the effect of N treatments interacting with P_2O_5 treatments; P_{it} represents the level of P_2O_5 applied on plot *i* in site-year t; N_{it} represents the level of nitrogen applied on plot *i* in site-year *t*, v_t is error term to the capture the site-year random effect; and ε_{it} is the usual error term. Symbols v_t and ε_{it} are assumed to be independent and normally distributed with means of zero and variances σ_v^2 and σ_ϵ^2, respectively.

The D'Agostino-Pearson K^2 test (Omnibus test) was used to test to see if our data deviated from normality, either due to skewness ($\sqrt{b_1}$) or kurtosis (b_2) (D'Agostino, Belanger, and D'Agostino, Jr., 1990). The results of this test show that the null hypothesis could not be rejected (*P* = 0.1247). In addition, a likelihood ratio (LR) test was used to test the hypothesis that residuals in the agronomic and economic models estimated with equation 2 are homoskedastic across N and P_2O_5 treatments (Biermacher et al., 2009; Boyer et al., 2011). The test statistics (LR) follow a chi-square (X^2) distribution with degrees of freedom equal to the number of imposed restrictions (two in this case). The results of the LR test, indicated that the null hypothesis of homoskedasticity (equal variances) across fertilizer rates was rejected (LR = 27.6; X^2=5.99; j=2). As a result, corrections for variances across fertilizer rates were made to each of the models estimated using equation 2 using a repeated measures approach in SAS. Lastly, the term used to evaluate the effect of the interaction between N and P_2O_5 specified in equation 2, β_3, was found to be not significantly different from zero (P = 0.9491) for yield, (P = 0.9426) for gross revenue, (P = 0.9492) for total cost, (P = 0.9491) for net return, and (P = 0.3626) for breakeven price. Therefore, the agronomic and economic models specified in equation 2 were re-estimated without the N x P_2O_5 interaction term.

RESULTS

Agronomic

Variation of yields across locations and years were evident in table 1. A greater amount of feedstock was produced at the Ardmore site in 2009 and 2010 compared to 2008. At the Waurika site, a greater quantity of feedstock was produced in 2008 and 2010 than in 2009, primarily due to differences in rainfall between those years. On average, the Waurika site realized greater quantities of feedstock than the Ardmore location. The maximum yield was 17.6 Mg ha^{-1} at Waurika in 2010 and the lowest yield was 3.3 Mg ha^{-1} at Ardmore in 2008. On average, switchgrass yield responded to both N and P_2O_5fertilizer. Yield was greater for each level of P_2O_5 application when N was applied. Conversely, in the absence of N, switchgrass did not appear to increase with phosphorus application.

Results show that switchgrass yield was affected by P_2O_5 ($P < 0.0001$) and N ($P = 0.0082$) applications (Table 2). On average, over site-years, switchgrass yield increases from 10.5 to 12.3 Mg ha^{-1} (a 17% increase) with the 101-kg ha^{-1} P_2O_5 treatment. The results also showed that there was no significant difference between mean yields obtained from the 0, 34, and 67 kg ha^{-1} P_2O_5 treatments. In addition, yield increased from 9.4 Mg ha (0 kg treatment) to 12.6 Mg ha with 135-kg N treatment, or by 34%.

Economic

The effects of N and P_2O_5 on costs, revenues, net returns and breakeven price are reported in Table 2. Results show that N ($P <0.0001$) and P_2O_5 ($P< 0.0001$) significantly affected total cost of production. Total estimated costs were \$840, \$887, \$934, and \$1,011 ha^{-1} with the 0, 34, 67, and 101 kg P_2O_5 ha^{-1} treatments, respectively. In addition, due to cost of nitrogen and cost of baling, total cost estimated with 135 kg ha^{-1} N application was significantly higher (34%) than the total cost for the 0 kg ha^{-1} level of N.

Results showed that N ($P < 0.0001$) and P_2O_5 ($P = 0.0215$) significantly affected gross revenues. Total estimated revenues were \$1,154, \$1,184, \$1,189 and \$1,352 ha^{-1} for the 0, 34, 67, and 101 kg ha^{-1} P_2O_5 treatments, respectively. Average revenue increased by 17% (or \$345 ha^{-1}) with 135 kg ha^{-1} of N treatment because yield increased by 34% at this level.

Expected net return (assuming a base feedstock price of \$110 Mg ha^{-1}) was affected by the level of N ($P = 0.0410$); however, the effect if $P_2O_5$was not significant ($P = 0.5160$), suggesting that the average value of the 17% increase in yield realized from the 101-kg P_2O_5 treatment was less than the average cost of the $P_2O_5$and its application. In addition, at a feedstock price of \$110 Mg ha^{-1} and budgeted price of \$1.28 kg^{-1} of N and \$1.17 kg^{-1} of P_2O_5, we found that producers would earn an additional \$77 ha^{-1} with the 135-kg treatment compared to the 0-kg treatment. This supports many other findings that producers of this region would be better off by applying N compared to not applying N. The results also showed that producers would not be better off applying any phosphorus to switchgrass in phosphorus-deficient soils, at least based on the three years of data evaluated in this study.

The breakeven price of feedstock was affected by N application (P= 0.0455), but not affected by the level of P_2O_5 (P= 0.3825). The breakeven prices for the 0, 34, 67, and 101 kg P_2O_5 ha^{-1} treatments were \$93, \$97, \$98, and \$95 Mg^{-1}, respectively. The breakeven price of feedstock was \$92 Mg^{-1} for the N application rate of 135 kg ha^{-1}. At \$92 Mg^{-1}, producers in this region can expect to earn negative net returns and, therefore, would likely not be interested in the switchgrass feedstock enterprise.

Table 3 summarizes how sensitive net returns are to expected changes in prices of P_2O_5, N, and the price of feedstock. Reductions (or increases) in the base price of phosphorus have no affect on the relative profitability between phosphorus rates. When a low price of phosphorus is used (\$0.77 kg^{-1}) the 101-kg treatment becomes \$36 ha more profitable than the base model. However, this difference is only numerically superior to the control treatment. At phosphorus prices equal to or greater than \$2.20 kg^{-1}, the profitability of the 101-kg treatment falls substantially below the control treatment. In the case where the price of phosphorus is high, holding all other prices constant, producers would not be inclined to apply it to their switchgrass crops.

Conversely, we found that the 135 $kg^{-1}$of N treatment would be statistically more profitable at prices of N is \$0.77 and \$ 1.28 kg^{-1}compared to the control treatment. There was, however, no statistical difference in profitability between the 135-kg and 0-kg treatments when the price of N was as high as \$2.20 kg^{-1}, but we did see a \$53 ha^{-1} numerical difference that favored the 135-kg treatment. Holding all other prices constant, it appears to be economical to apply N fertilizer to switchgrass in this region.

The results showed that for a feedstock price of \$83 Mg, profitability for most all treatments was essentially zero or less. At this price, producers will not be interested in growing switchgrass on their farms. In addition, for either of the three feedstock prices evaluated, there was no statistical difference in profitability for neither of the four P_2O_5 rates; however, a sizeable numerical difference existed between the control treatment and the 101-kg treatment for feedstock prices of \$110 and \$165 Mg^{-1}. Lastly, the results showed that for the base biomass price of \$110 Mg^{-1} and current market price of \$1.28 kg^{-1} of P_2O_5, it would not be economical to apply nitrogen at a price of nitrogen greater than \$2.34 kg^{-1}.

CONCLUSIONS AND LIMITATIONS

Economic information about how best to manage nitrogen and phosphorus nutrients for switchgrass feedstock production in phosphorus-deficient soils is limited. Results from a two-location, three-year agronomic trial conducted on phosphorus-deficient soils in south-central Oklahoma indicate that yield responds to applications of P_2O_5. However, the economic results showed that the average benefits from this response did not outweigh the average costs associated with phosphorus and phosphorus application. This results suggests that phosphorus-deficient soils do not seem to have the same impact on switchgrass profitability as they do for the profitability of other crops traditionally produced by farmers in this region. The results do support the findings of other published literature regarding the agronomic and economic benefits associated with supplying nitrogen fertilizer to growing switchgrass, even when produced in phosphorus-deficient soils. That is, it was found to be economical to apply 135 kg ha^{-1} of N, even though this rate doesn't necessarily reflect the economically optimal rate.

One limitation of this research is that the field experiments only included two levels of N and only four levels of P_2O_5 for three years. Additional N and P treatments would allow for the estimation of a continuous, multivariate response to phosphorus and nitrogen function that could then be used to determine the economically optimal rates of N and P that will maximizing the producer's profit function.

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Table 1- Switchgrass yield at Ardmore and Waurika for three years (2008-2010) over four replications.

	Nutrient applied (kg ha^{-1})			Yield (Mg ha^{-1})[†]		
Year	N	P_20_5	K_20	Ardmore	Waurika	Average
2008	0	0	135	4.0	12.1	8.1
	0	34	135	4.3	11.3	7.8
	0	67	135	3.3	10.4	6.9
	0	101	135	3.9	14.2	9.1
	135	0	135	6.4	13.1	9.8
	135	34	135	6.4	12.4	9.4
	135	67	135	6.4	12.1	9.3
	135	101	135	7.3	15.6	11.4
2009	0	0	135	7.4	10.1	8.7
	0	34	135	5.8	10.1	8.0
	0	67	135	5.8	9.0	7.4
	0	101	135	7.7	10.9	9.3
	135	0	135	14.3	7.5	10.9
	135	34	135	16.2	7.3	11.8
	135	67	135	15.9	9.4	12.6
	135	101	135	16.2	9.6	12.9
2010	0	0	135	7.6	12.6	10.1
	0	34	135	7.8	16.4	12.1
	0	67	135	9.2	16.1	12.6
	0	101	135	10.5	17.6	14.0
	135	0	135	15.3	15.3	15.3
	135	34	135	17.3	13.8	15.5
	135	67	135	17.2	14.6	15.9
	135	101	135	16.8	16.9	16.9
Average	0	0	135	6.4	11.6	9.0
	0	34	135	6.0	12.6	9.3
	0	67	135	6.1	11.8	9.0
	0	101	135	7.3	14.2	10.8
	135	0	135	12.0	12.0	12.0
	135	34	135	13.3	11.1	12.2
	135	67	135	13.2	12.0	12.6
	135	101	135	13.4	14.1	13.7

[†] Yields were collected after harvesting biomass once yr^{-1}in winter (December or January) at least 30 days after killing winter-frost.

Table 2- Average feedstock yield (Mg ha^{-1}), breakeven price (\$ Mg^{-1}), total cost (\$ ha^{-1}), total revenue (\$ ha^{-1}), and net return to labor, management and overhead (\$ ha^{-1}) at a feedstock price of \$110 Mg ha^{-1}.

Nutrient Rate (kg ha^{-1})	Yield (Mg ha^{-1})	Breakeven price (\$ Mg^{-1})	Total revenue (\$ ha^{-1})	Total cost (\$ ha^{-1})	Expected net return (\$ ha^{-1})
N = 0	9.4b†	99a	1048b	783b	264b
N = 135	12.6a	92b	1394a	1053a	341a
P_2O_5 = 0	10.5b	93	1154b	840d	314
P_2O_5 = 34	10.8b	97	1184b	887c	297
P_2O_5 = 67	11.0b	98	1189b	934b	255
P_2O_5 = 101	12.3a	95	1352a	1011a	341

† Means reported for N and P_2O_5 treatments for the same agronomic or economic variable marked with the same letter are not significantly different (LSD test, $\alpha = 0.05$).

Table 3. Net return to management and overhead for an incremental range of prices of N, P_20_5, and feedstock (\$ ha^{-1}).

Prices	N treatments (kg ha^{-1})			P_2O_5 treatments (kg ha^{-1})				
	0	135	P-value[†]	0	34	67	101	P-value
P_20_5 (\$ kg^{-1})								
0.77	284b[‡]	361a	0.0410	314	307	295	377	0.2783
1.17 (base)	264b	341a	0.0410	314	297	255	341	0.5160
2.20	209b	286a	0.0410	314	257	195	226	0.0884
N (\$ kg^{-1})								
0.77	264b	412a	0.0001	349	329	303	371	0.5160
1.28 (base)	264b	341a	0.0410	314	297	255	341	0.5160
2.20	211	264	0.1588	249	228	203	271	0.5160
Biomass (\$ Mg^{-1})								
83	2	-7	0.7155	25	-2	-33	-1	0.3562
110 (base)	264b	341a	0.0410	314	297	255	341	0.5160
165	788b	1037a	0.0001	890	883	868	1009	0.2285

[†] P-values reported are from the Type 3 F-test for fixed effects.

[‡] Means reported for N and P_2O_5treatmentswith the same combination of prices marked with the same letter are not significantly different (LSD test, $\alpha = 0.05$).

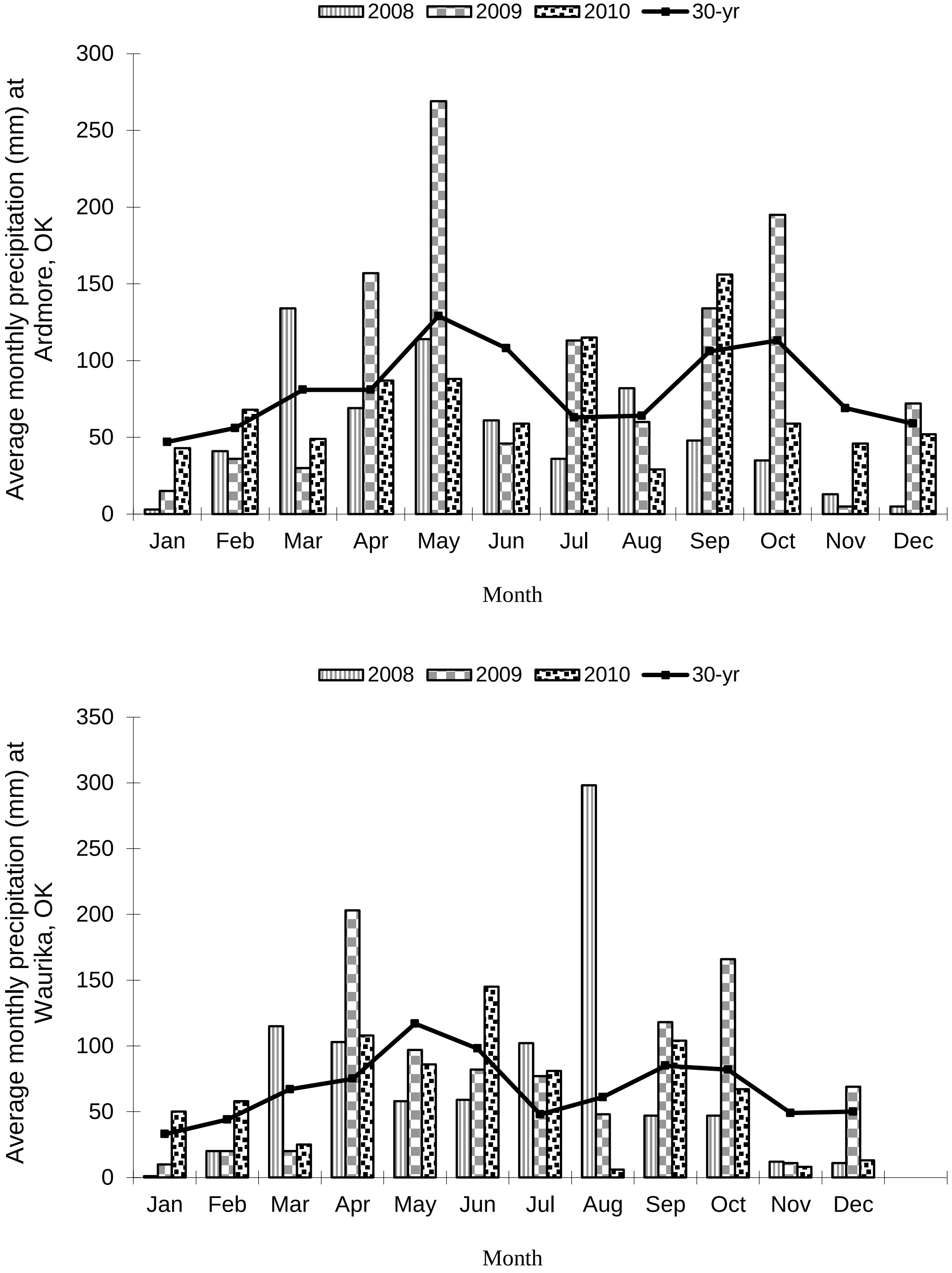

Figure 1: Precipitation observed in 2008–2010and average across 30-yr (1971-2000) at Ardmore, OK and Waurika, OK (Oklahoma Mesonet, 2011).

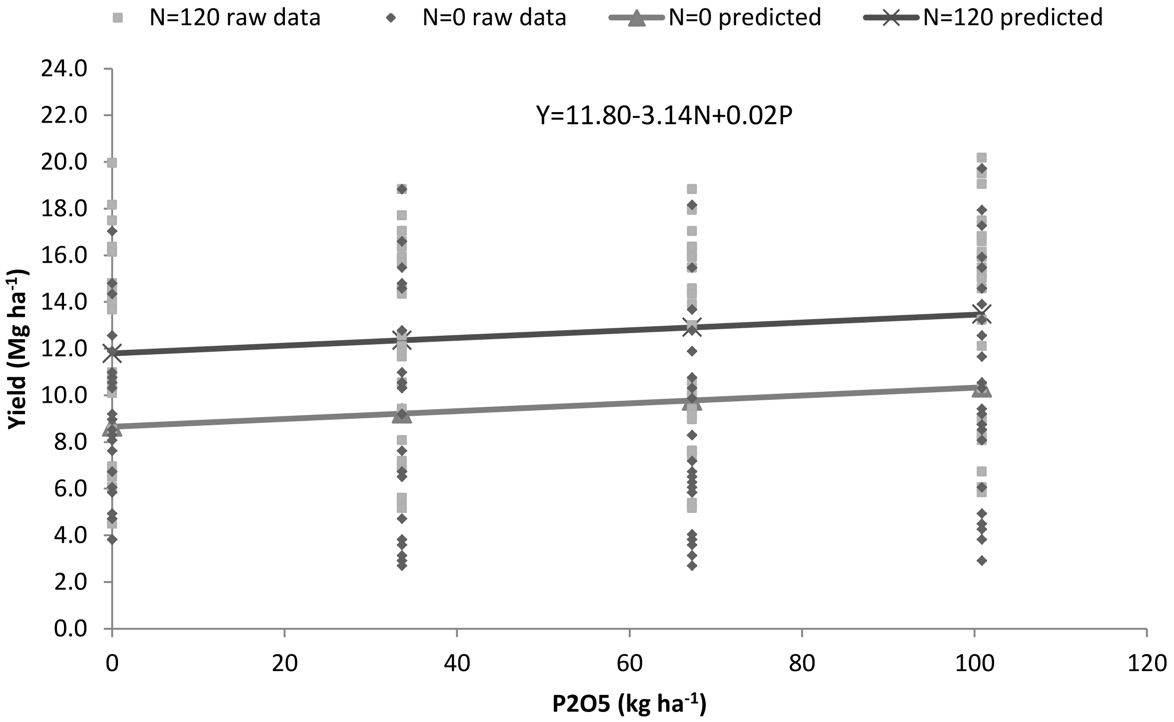

Figure 2. Effects of N and P_2O_5 fertilization on switchgrass biomass yield (Mg ha^{-1}). Predicted yield equation were estimated using mixed model where phosphorus was treated as continuous variable.