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# Economic Evaluation of Switchgrass Feedstock Production Systems Tested in Potassium-Deficient Soils

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**Abstract** Limited information is available about the economic benefits and costs associated with managing switchgrass (*Panicum virgatum* L.) produced for bioenergy feedstock in the K-deficient soils common in the southern Great Plains. The objectives of this study were to determine the most economical production system for harvesting and managing N and K fertilizations on switchgrass stands and to determine how sensitive the results are to various feedstock and fertilizer market price scenarios. A 4-year agronomic field experiment was conducted on a K-deficient site in South Central Oklahoma; the treatments included two harvest systems (summer and winter (SW) and winter only (W)), two N rates (0 and 135 kg ha$^{-1}$), and two K rates (0 and 67 kg ha$^{-1}$). Enterprise budgeting techniques and mixed ANOVA models were used to determine and compare the effects of eight harvest/N/K systems on yield, total cost, revenue, and net return. The harvest/N/K systems evaluated included SW/0/0, SW/0/67, SW/135/0, SW/135/67, W/0/0, W/0/67, W/135/0, and W/135/67. Results revealed the SW/135/67 system produced significantly ($P>0.0001$) greater average yield compared to the other systems; however, the SW/0/0 system was the most ($P>0.0001$) economical, realizing an average net return of \$415 ha$^{-1}$. Compared to the base–case net return of the SW/0/0 system, the value of the additional yield generated with the SW/135/67 system was less than the costs associated with the extra nutrients and additional harvest activity. For feedstock prices greater than \$110 Mg$^{-1}$, the most economical system shifted from the SW/0/0 to favor the SW/135/67 system.

**Keywords** Bioenergy feedstock · Economics · Nitrogen fertilizer · Potassium-deficient soil · Potassium fertilizer · Switchgrass

## Introduction

Switchgrass (*Panicum virgatum* L.) has been identified by production scientists and public policy makers as a leading source of bioenergy feedstock for the large-scale conversion into biofuels in the southern Great Plains—a region that has a comparative advantage in growing native perennial forages for livestock, wildlife, and conservation programs [1]. Extensive soil testing has revealed that a substantial percentage of acres in the southern Great Plains are deficient in potassium (K), primarily those in the eastern areas that are comprised of sandy soils and receive greater than 889 mm of rainfall each year [2]. At present, most switchgrass fertilizer management studies have mainly focused on the benefits and costs associated with nitrogen (N) fertilizer as the primary limiting nutrient [3–5] and a few studies have focused on phosphorus (P) fertilizer [1, 6, 7]. However, little information is available regarding the costs and benefits associated with N and K fertilization on switchgrass produced in K-deficient soils.

Potassium is important for growth and development of plants, necessary for the activation of several enzymes, helps break down and translocate starches, increases water use efficiency, essential for protein synthesis, increases photosynthesis, increases disease resistance in plants, and can hamper plant growth if deficient [8–10]. Despite the crucial role K has

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on plant growth and development, few studies have evaluated the response of switchgrass to K fertilizer, and most of those that did were conducted inside a controlled greenhouse environment. For instance, Friedrich, Smith, and Schrader [11] concluded from their greenhouse experiments that dry matter yield increased with N but was not affected by K fertilization. In another greenhouse experiment, it was revealed that switchgrass herbage dry matter yield was very responsive to N but was not influenced by K fertilization [12]. In another greenhouse study, the authors reported that no additional yield response was found due to additional treatments of K fertilizer and suggested that warm-season grasses such as switchgrass may have a lower requirement for K fertilizer [13]. Conversely, small-plot field trials conducted on switchgrass grown as a dedicated bioenergy crop in Oklahoma reported that under one- and two-cut harvests, switchgrass produced greater yield when fertilized with both N and K compared to only N, only K, and zero fertilizer check treatments [9]. It is important to point out that none of these studies considered the economic benefits and costs associated with K application for switchgrass production.

Several agronomic researchers have shown that switchgrass plants remove large quantities of K from the soil when harvested [14, 15]. Moreover, research also reported that K removed by harvested biomass was affected by harvest timing and frequency [14, 16–18]. Compared to switchgrass harvested after plant senescence, harvesting at plant physiological maturity remove greater quantities of K from the soil [14]. In addition, it was reported that if harvest activity is delayed until after plant senescence, some of the K will be recycled to belowground tissues and will minimize the need for their replacement [14, 16]. A study conducted in Oklahoma reported that high K uptake by switchgrass occurred with three harvests (May, mid-July, and September) each year and the least occurred with only a single harvest (at the end of September), after plant senescence [16].

Agronomic results for studies that evaluated single- and multiple-cut harvest systems for switchgrass are mixed, primarily due to differences in growing conditions (i.e., rainfall and soil type) between the study sites. For instance, a number of studies evaluating switchgrass as a dedicated bioenergy crop report that a one-cut harvest system produced greater average yield (and profit) compared to a two-cut harvest system [3, 4]. In contrast, other studies reported the greatest yields were realized with two- and three-cut systems [14, 16]. However, even though production systems that include multiple harvests per year can produce greater feedstock yield, they have also been shown to deplete soil fertility because they remove greater quantities of nutrients, especially N and K, from the soil. This situation might have further negative implications for switchgrass that is produced in soils that are deficient in K.

A better understanding of the economic relationships between alternative harvest timings and N and K fertilizer applications and feedstock production in K-deficient soils is important for farm producers that may be interested in producing switchgrass as a bioenergy crop. The objectives of this study were to determine the most economical production system for harvesting and managing N and K fertilizations of switchgrass stands produced in K-deficient soils, and to determine how sensitive the results are to various feedstock and fertilizer market price scenarios.

## Material and Methods

### Agronomic

Switchgrass cv. Alamo was established in 2007 at the Noble Foundation Pasture Demonstration Farm (PDF) in Carter County (34°22′N; 97°21′W) near the community of Ardmore, Oklahoma. Soil at the experimental site was classified as Chickasha loam (fine-loamy, mixed, active, and thermic Udic Argiustolls). Extensive soil testing at the site confirmed significant deficiency in K fertilizer. Soil chemical and physical properties were measured at 0–15 and 15–30 cm soil depths before initiation of the N and K experiment and are presented in Table 1. Test results showed soil K levels (Mehlich III) at PDF were 162 and 165 kg ha$^{-1}$ when measured at 0–15 and 15–30 cm soil depths. According to the Oklahoma State Extension Service [19], soil is deficient in K if soil K level is below 224 kg ha$^{-1}$ for warm-season grasses such as bermudagrass (*Cynodon dactylon* (L.) Pers.) and old world bluestem (*Bothriochloa ischaemum* (L.)) that are common to the region and may be deficient for switchgrass as well.

The experiment was a randomized complete block design with a factorial arrangement of eight treatments and four replications. The treatments included two harvest systems, two N rates, and two K rates. Harvest treatments included either a single harvest after plant senescence in the winter (W)

**Table 1** Soil test results at the Pasture Demonstration Farm (PDF) experimental location, Ardmore, OK

| Soil property† | Soil depth (cm) | |
|---|---|---|
| | 0–15 | 15–30 |
| pH | 5.7 | 6.9 |
| Organic matter, % | 2.0 | 1.4 |
| $NO^3$-N, kg ha$^{-1}$ | 11 | 2.2 |
| P, kg ha$^{-1}$ | 537 | 78 |
| K, kg ha$^{-1}$ | 162 | 165 |
| Ca, kg ha$^{-1}$ | 1,269 | 2,414 |
| Mg, kg ha$^{-1}$ | 475 | 856 |
| Na, kg ha$^{-1}$ | 34 | 69 |

†Soil test done in April 23, 2007, prior to initiation of the experiments

or a two-cut harvest system with the first in the summer during onset of reproduction (boot stage) followed by a second in the winter after a hard freeze (SW). An N treatment of either 0 or 135 kg ha$^{-1}$ was applied in the form of urea (46-0-0) during greening in the spring of each production year (2008–2011), and a K treatment of either a 0 or 67 kg of K ha$^{-1}$ was applied in the form of $K_2O$ (0-0-60) in spring of each year starting in 2007.

Before stand establishment, the experimental plots were disced twice in April 2007, and a single application (2.34 L ha$^{-1}$) of glyphosate *N*-(phosphonomethyl) glycine was applied across the plots to suppress weed growth. Fields were cultivated immediately before switchgrass seeding using a field cultivator on May 18, 2007. Initial soil testing ensured adequate levels of P were present (Table 1) for warm season grasses (e.g., bermudagrass and old world bluestem) that are common to the region [20]. Therefore, P was not applied to the plots in the establishment year. Alamo switchgrass was seeded at 5.6 kg pure live seed per hectare using a SS-series Brillion seeder (Brillion farm equipment, Brillion, WI, USA). To reduce competition for light from tall annual broadleaf weeds (primarily *Amaranthus retroflexus* L.) that emerged after switchgrass seeding, all plots were custom mowed at a≈20-cm height in mid-July and treated with a single application of herbicide 2,4-D Amine (2,4-dichlorophenoxyacetic acid, dimethyl amine) at 3.51 L ha$^{-1}$ 2 weeks later. Blanket applications of $P_2O_5$ (0-46-0) were broadcast in the beginning of each production year on all plots at a rate of 67 kg ha$^{-1}$ year$^{-1}$ to ensure that P would not limit yield over the life of the study.

All plots were harvested in 2008, 2009, 2010, and 2011 but not harvested in 2007 to maintain stand longevity [20]. Summer harvests were conducted on 7, 15, 19, and 8 July and winter harvests were conducted after plant senescence on 17, 11, 17, and 9 December for the years 2008, 2009, 2010, and 2011, respectively. Either a Carter (Brookston, IN) or a HEGE (Colwich, KS) forage harvester was used to perform harvesting operations at a 10-cm stubble height. For comprehensive details regarding the field experiment, see Kering et al. [9].

## Economic

Enterprise budgeting procedures [21] were used to calculate expected values for revenue, total cost, and net return for the eight alternative harvest/N/K feedstock production systems for each year. The eight harvest/N/K systems are represented by the following: SW/0/0, SW/0/67, SW/135/0, SW/135/67, W/0/0, W/0/67, W/135/0, and W/135/67. The letters represent the harvest system (SW for summer and winter, and W for winter only), the first number in each system represents the level of N applications (in kilograms per hectare per year) and the second represents the level of K applications (in kilograms per hectare per year). Charges related to owner's labor, management, and overhead are assumed to be the same across the eight harvest/N/K systems.

Budgeting procedures include the annual prorated cost associated with switchgrass establishment (i.e., total establishment cost amortized over 10 years at 6.25 APR [1, 22]), and the annual costs for nutrient and nutrient application and harvesting activity (i.e., cutting, raking, baling and hauling, and stacking at the farm gate). Establishment costs include field operations for seeding and seed bed preparation (discing, field cultivation, and seeding with a conventional Brillion seeder), cost of seed, pesticide and fertilizer application, and land rental. These costs did not vary across production systems.

Annual production cost included fertilizer (N and K) as well as costs for their applications and costs of harvesting activities (mowing, raking, baling and hauling, and stacking large (680 kg) square bales at the farm gate). Costs of mowing and raking were fixed per hectare, but the cost of baling and hauling and stacking varied by yield for each system. Field operations for seed bed preparation and planting, fertilizer application, and harvesting activity were assumed to be managed by custom operation providers and their prices obtained from state average custom rates published by Doye and Sahs [23]. Local market prices were used for seed, fertilizer, pesticides, and land rental rates. Prices and costs for all inputs and field operations are reported in Table 2.

At present, there are no large-scale biorefineries located in the southern Great Plains and, therefore, there is no established market price for switchgrass feedstock produced as a dedicated bioenergy crop [24, 25]. To circumvent this issue, we utilize the feedstock market price scenarios reported in Haque et al. [1] who utilized a base–case price of \$83 Mg$^{-1}$, a low price of \$55 Mg$^{-1}$, and a high feedstock price scenario of \$110 Mg$^{-1}$. This range in feedstock price scenarios provides us the opportunity to illustrate when the profitability of all the switchgrass production systems tested are negative and when the relative profitability between the systems that utilize more nitrogen become favored compared to those utilizing zero fertilizer. In addition, the relative economics of the eight production systems were evaluated for both low (\$0.77 kg$^{-1}$) and high (\$2.20 kg$^{-1}$) market prices scenarios for N and K nutrients, respectively. The low and high price scenarios used in this study reflect the uncertain volatility of fertilizer markets over the past several years. For instance, in 2007, the local market price in South Central Oklahoma for N fertilizer approached \$2.05 kg$^{-1}$, and in July of 2013, the local market price of N declined to \$0.82 kg$^{-1}$.

## Statistical Analysis

Agronomic and economic data were analyzed using random effects mixed ANOVA models to estimate the effects of harvest/N/K production systems on yield, total cost, total

**Table 2** Costs and prices for fertilizer and fertilizer application, seed, herbicide, custom machinery operation, land rental, interest rates, and expected stand life assumed in the analysis

| Variables | Price† |
|---|---|
| Nitrogen (N) (46-0-0), \$ kg$^{-1}$ | 1.43 |
| Phosphorus (P) (0-46-0), \$ kg$^{-1}$ | 0.99 |
| Potassium (K) (0-0-60), \$ kg$^{-1}$ | 1.17 |
| Switchgrass seed (Alamo), \$ kg$^{-1}$ | 33.00 |
| Herbicide (Glyphosate), \$ L$^{-1}$ | 3.70 |
| Herbicide (2,4-D Amine), \$ L$^{-1}$ | 3.36 |
| Custom fertilizer application, \$ ha$^{-1}$ | 10.43 |
| Custom herbicide application, \$ ha$^{-1}$ | 13.47 |
| Custom rate for discing, \$ ha$^{-1}$ | 25.08 |
| Custom rate for field cultivating, \$ ha$^{-1}$ | 21.30 |
| Custom rate for seed planting, \$ ha$^{-1}$ | 12.85 |
| Custom rate for mowing, \$ ha$^{-1}$ | 26.54 |
| Custom rate for raking, \$ ha$^{-1}$ | 11.84 |
| Custom rate for bailing, \$ ha$^{-1}$ | 42.63 |
| Custom rate for hauling and stacking at farm gate, \$ ha$^{-1}$ | 14.28 |
| Land rental rate, \$ ha$^{-1}$ | 123.55 |
| Switchgrass expected stand life, years | 10 |
| Interest rate for long-term capital, % | 6.25 |
| Annual operating interest rate, % | 6.75 |

†Market prices for N, P, K, seed, herbicides were obtained from a local farm input supplier in August 2012 and custom rates were obtained from Doye and Sahs [22]

revenue, and net return using the PROC MIXED procedure in SAS [1, 26, 27]. Mathematically, the ANOVA model is expressed as follows:

$$Y_{itr} = a + \sum_{j=1}^{J-1} \beta_j S_{jitr} + \upsilon_t + \eta_r + \lambda_{tr} + \varepsilon_{itr} \tag{1}$$

where $Y_{itr}$ represents agronomic and economic variables (i.e., feedstock yield (in megagrams per hectare), total cost (in dollars per hectare), gross revenue (in dollars per hectare), and net return (in dollars per hectare)) on plot $i$ ($i=1,\ldots,$ I) in year $t$ ($t=1,\ldots,4$) on block (replication) $r$ ($r=1,\ldots,4$); $\alpha$ is the intercept; $\beta$ is the effect associated with feedstock production system $j$ ($j=1,\ldots,8$); $S_{jitr}$ represents feedstock production system $j$ on plot $i$ in year $t$ on block $r$; $\upsilon_t$ is an error term representing the year random effect; $\eta_r$ is an error term representing the block (replication) random effect; $\lambda_{tr}$ is an random error term that captures the interaction between year and block (replication); and $\varepsilon_{itr}$ is the usual error term. Symbols $\upsilon_t$, $\eta_\mathrm{r}$, $\lambda_\mathrm{tr}$, and $\varepsilon_{itr}$ are assumed to be independent, identical, and normally distributed with means of zero and variances of $\sigma_\upsilon^2$, $\sigma_\eta^2$, $\sigma_\lambda^2$, and $\sigma_\varepsilon^2$, respectively.

For each of the four ANOVA models estimated, production system was treated as a fixed effect while year and block (replication) was treated as random. Because block represents the replication, their effects are considered random because the blocks in the experiment are only a small subset of the larger set of blocks over which inference about treatment means is to be made. A likelihood ratio (LR) test was used to test the null hypothesis of no random effect associated with (1) year, (2) replication, and (3) the interaction between year and replication [1, 28]. The LR test was performed based on the log-likelihood value obtained from both restricted and unrestricted models, and the test statistics follows a chi-square ($\chi^2$) distribution with degrees of freedom equal to the number of imposed restrictions. LR test failed to reject the null hypothesis of no random effects for the interaction between replication and year. However, the hypotheses of no random effects associated with year (LR=139.2, $\chi^2$=3.84; $j$=1) and replication (LR=5.62, $\chi^2$=3.84; $j$=1) were rejected.

Previous research has shown that crop yield data are often times skewed and do not follow a normal distribution [29–31]. The D'Agostino–Pearson K$^2$ test was used to see if the data were normally distributed [1, 32]. The results of the D'Agostino–Pearson K$^2$ test revealed that the null hypothesis could not be rejected ($P$=0.11635), indicating no corrections are needed to be made, since the data were found to be normally distributed.

Experimental data involving yield responses to fertilizer treatments also tend to exhibit heteroskedastic variances (i.e., greater yield variability associated with greater fertilizer rates) [32, 33]. A LR test was used to test the null hypothesis that variances are homoscedastic across N and K fertilizer treatments [28, 33, 34]. The results of the LR test revealed the presence of heteroskedasticity across fertilizer rates (LR= 41.2; $\chi^2$=5.99; $j$=2) and, as a result, a REPEATED statement was used with the PROC MIXED procedure for each model (i.e., yield, total cost, revenue, and net return) to control for heteroskedasticity by allowing the error terms in the model to vary by N and K fertilizer rates [33].

Fisher's protected $F$ tests were used to test the null hypotheses of no significant difference between production systems for the yield, total cost, revenue, and net return models estimated. The formal equations representing the four null hypotheses tested are represented mathematically as follows:

$$\mathrm{H}_0 : \beta_1{}^Y = \beta_2{}^Y = \ldots = \beta_j{}^Y \tag{2}$$

$$\mathrm{H}_0 : \beta_1{}^C = \beta_2{}^C = \ldots = \beta_j{}^C \tag{3}$$

$$\mathrm{H}_0 : \beta_1{}^R = \beta_2{}^R = \ldots = \beta_j{}^R \tag{4}$$

$$\mathrm{H}_0 : \beta_1{}^{NR} = \beta_2{}^{NR} = \ldots = \beta_j{}^{NR} \tag{5}$$

where, $Y$, $C$, R, and $NR$ represent yield, total cost, gross revenue, and net return, respectively.

Least significant difference tests were then used to rank economic performance of each production system for each of the four ANOVA models evaluated [1].

## Results and Discussion

Feedstock yield, total production costs, gross revenues, and net returns for the eight harvest/N/K production systems are presented in Table 3. The SW/135/67 system produced, on average, 19.2 Mg ha$^{-1}$, which was significantly ($P<0.0001$) greater yield than the other seven systems, and 25 % greater than the SW/0/0 system (i.e., 19.2 Mg ha$^{-1}$ compared to 15.4 Mg ha$^{-1}$). In addition, an 18 % (12.4 Mg ha$^{-1}$ to 14.6 Mg ha$^{-1}$) increase in yield was observed with the W/135/67 system compared to the W/0/0 system. These results suggest that switchgrass yield responded in a statistically significantly way to joint applications of N and K fertilization for one- and two-cut harvest systems. Moreover, the results revealed that the SW/135/67 system produced 32 % greater yield compared to the W/135/67 system, which suggests that the two-cut (summer and winter) harvest system responded better than the one-cut (winter only) harvest system when both N and K nutrients were applied. This result was similar to a report that harvesting switchgrass twice per year (once after boot stage and again after frost) with N, P, and K applications produced the greatest biomass yield [14]. Furthermore, we found that both systems that received only K fertilizer (i.e., the SW/0/67 and W/0/67 systems) did not realize greater yield compared to the systems that received no fertilizer treatments (i.e., the SW/0/0 and W/0/0 systems). This result was similar to a previously published agronomic study conducted on experimental plots of bermudagrass where no response to K was observed in K-deficient soils [35].

There was no statistically significant difference between the yields of the SW/0/0 and SW/135/0 systems and the yields of the W/0/0 and W/135/0 systems. This suggests that systems with N applications did not realize statistically greater yields

**Table 3** Average feedstock yield and expected values for production costs, gross revenues, and net returns for eight harvest/N/K feedstock production systems

| Yield and economic measurements | Harvest/N/K feedstock production system | | | | | | | | P>F‡ |
|---|---|---|---|---|---|---|---|---|---|
| | SW/0/0† | SW/0/67 | SW/135/0 | SW/135/67 | W/0/0 | W/0/67 | W/135/0 | W/135/67 | |
| Feedstock yield (Mg ha$^{-1}$) | 15.4b§ | 13.7c | 16.0b | 19.2a | 12.4d | 13.4cd | 13.4cd | 14.6bc | <0.0001 |
| Establishment costs: | | | | | | | | | |
| Seedbed preparation (\$ ha$^{-1}$) | 71.46 | 71.46 | 71.46 | 71.46 | 71.46 | 71.46 | 71.46 | 71.46 | – |
| Pesticide application (\$ ha$^{-1}$) | 47.37 | 47.37 | 47.37 | 47.37 | 47.37 | 47.37 | 47.37 | 47.37 | – |
| Switchgrass seed and seed establishment (\$ ha$^{-1}$) | 198.18 | 198.18 | 198.18 | 198.18 | 198.18 | 198.18 | 198.18 | 198.18 | – |
| Fertilizer application (K) (\$ ha$^{-1}$)¶ | 49.72 | 49.72 | 49.72 | 49.72 | 49.72 | 49.72 | 49.72 | 49.72 | |
| Land rental: first year (\$ ha$^{-1}$) | 123.55 | 123.55 | 123.55 | 123.55 | 123.55 | 123.55 | 123.55 | 123.55 | – |
| Custom mowing (\$ ha$^{-1}$) | 26.54 | 26.54 | 26.54 | 26.54 | 26.54 | 26.54 | 26.54 | 26.54 | |
| Total establishment cost (\$ ha$^{-1}$) | 516.82 | 516.82 | 516.82 | 516.82 | 516.82 | 516.82 | 516.82 | 516.82 | – |
| Establishment cost amortized @ 6.25 % over 10 years (\$ ha$^{-1}$) | 71.05 | 71.05 | 71.05 | 71.05 | 71.05 | 71.05 | 71.05 | 71.05 | – |
| Annual costs: | | | | | | | | | |
| Fertilizer application (N, P, and K) (\$ ha$^{-1}$) | 66.72 | 145.30 | 269.89 | 348.47 | 66.72 | 145.30 | 269.89 | 348.47 | – |
| Cutting, raking, baling and hauling, and stacking (\$ ha$^{-1}$) | 599.57 | 540.85 | 619.97 | 727.17 | 459.16 | 491.88 | 490.67 | 531.57 | – |
| Land rent: years 2–10 (\$ ha$^{-1}$) | 123.55 | 123.55 | 123.55 | 123.55 | 123.55 | 123.55 | 123.55 | 123.55 | – |
| Interest on operating capital (\$ ha$^{-1}$) | 2.59 | 5.64 | 10.48 | 13.53 | 2.59 | 5.64 | 10.48 | 13.53 | – |
| Total production costs (\$ ha$^{-1}$) | 863de | 886d | 1,095b | 1,284a | 723f | 837e | 966c | 1,088b | <0.0001 |
| Gross revenue (\$ ha$^{-1}$)# | 1,278b | 1,137c | 1,328b | 1,594a | 1,029d | 1,112 cd | 1,112 cd | 1,212bc | <0.0001 |
| Net return (\$ ha$^{-1}$) | 415a | 251bc | 233c | 310b | 306b | 275bc | 146d | 124d | <0.0001 |

† The letters represent harvest system, the first number is kg of N ha$^{-1}$ and second number is kg of $K_2O$ ha$^{-1}$

‡ $P$ values are based on Fisher's protected $F$ tests

§ Means reported for yield, total cost, gross revenue, and net return for the feedstock production systems within a row marked with the same letter are not significantly different based on an LSD test ($P<0.05$)

¶ Costs of fertilizer was estimated assuming a base–case N price of \$1.43 kg$^{-1}$ and a $K_2O$ price of \$1.17 kg$^{-1}$

# Revenue was calculated using a base–case feedstock price of \$83 Mg$^{-1}$

than systems without N applications, which is in contrast to what was found by previous studies [7, 14]. However, we point out that these studies were not conducted in K-deficient soils. This result seems to suggest that switchgrass requires joint applications of N and K fertilizers in order to achieve a significant yield response in K-deficient soils.

Total production costs were significantly ($P<0.0001$) affected by harvest/N/K production system. Estimated total cost was \$1284 ha$^{-1}$ for the SW/135/67 system and was greater than the other seven production systems. Total production cost for this system included \$71.05 (6 % of the total) for establishment, \$348.47 (27 % of the total) for fertilizer and fertilizer application, \$727.17 (56 % of the total) for harvesting, \$123.6 (10 % of the total) for land rental, and \$13.53 (1 % of the total) for interest on operating capital. Moreover, total cost increased by 78 % for the SW/135/67 system compared to the least cost system (W/0/0), indicating that the cost of fertilizer and cost of harvesting both play a crucial role in producing bioenergy feedstock from switchgrass.

The results for the base–case market price scenario (i.e., feedstock, N and P prices of \$83 Mg$^{-1}$ and \$1.43 and \$1.17 kg$^{-1}$, respectively) indicate that net returns were significantly affected ($P<0.0001$) by harvest/N/K systems, and the SW/0/0 system realized the greatest net return (\$415 ha$^{-1}$) amongst all systems. It is noteworthy to point out that the SW/135/67 and the W/0/0 systems were numerically the second and third most economical systems, earning \$310 and \$306 ha$^{-1}$, respectively. Even though SW/135/67 realized a greater yield than the SW/0/0 system, the SW/135/67 system incurred an even greater total cost compared to the SW/0/0/ system. That is, for the base–case price of \$83 Mg$^{-1}$, the value of the additional revenue from the yield advantage obtained with the SW/135/67 system did not outweigh the additional costs associated with 135 and 67 kg ha$^{-1}$ applications of N and K and the extra harvest costs associated with this system.

At first glance, this result suggests that producers growing switchgrass in K-deficient soils would be better off economically to cut, rake, bale and haul, and stack feedstock twice per growing season (i.e., once at plant maturity and again after a hard freeze) and not apply N or K fertilizers. Agronomically, however, the adoption of a system that does not allow for fertilizer application and replacement is likely not sustainable in the long-run because switchgrass plants harvested in the summer at plant maturity, prior to plant senescence, have been shown to remove (i.e., mine) significant quantities of N and K nutrients from the soil [14, 36]. Because of the nutrient removal issue surrounding the two-cut system, the W/0/0 system that was found to be statistically no different economically than the SW/135/67 system might be more sustainable in the long run than the SW/0/0 system. Unfortunately, long-term yield response data to N, P, and K fertilizers for switchgrass trials evaluated in K-deficient soil in the southern Great Plains do not exist, so the long-term plant performance (and variation in performance) is not well understood like it is for other more traditional crops produced in the region.

Expected values for net returns by harvest/N/K system for a range of alternative price scenarios for feedstock, N, and K are presented in Table 4. Overall, the relative results were most sensitive to the price of feedstock. For instance, regardless of the prices of N and K fertilizers, net returns for all eight harvest/N/K systems were negative for a price of feedstock equal to \$55 Mg$^{-1}$. For the base–case N and P fertilizer prices

**Table 4** Expected net return to owner's labor, management, and overhead for eight harvest/N/K feedstock production systems for a range of price scenarios (SC1 to SC9) for feedstock, N and K (\$ ha$^{-1}$)

| Price Scenario[‡] | Prices | | | Harvest/N/K feedstock production system | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Feedstock \$ Mg$^{-1}$ | N \$ kg$^{-1}$ | K \$ kg$^{-1}$ | SW0/0[†] | SW0/67 | SW135/0 | SW135/67 | W0/0 | W0/67 | W135/0 | W135/67 | P>F[‡] |
| SC1 | 110 | 0.77 | 0.77 | 839ab[§] | 653cd | 767bc | 955a | 647d | 667cd | 600d | 638cd | <0.0001 |
| SC2 | 110 | 1.43 | 1.17 | 839a | 625bc | 674b | 834a | 647b | 639bc | 507d | 518cd | <0.0001 |
| SC3 | 110 | 2.20 | 2.20 | 839a | 553b | 566b | 654b | 647b | 567b | 399c | 338c | <0.0001 |
| SC4 | 83 | 0.77 | 0.77 | 415a | 275bc | 324b | 425a | 306b | 298bc | 231c | 237bc | <0.0001 |
| SC5 | 83 | 1.43 | 1.17 | 415a | 251bc | 233c | 310b | 306b | 275bc | 146d | 124d | <0.0001 |
| SC6 | 83 | 2.20 | 2.20 | 415a | 175cd | 124d | 125cd | 306b | 198c | 31e | −64f | <0.0001 |
| SC7 | 55 | 0.77 | 0.77 | −12a | −103d | −118de | −105cde | −38b | −71c | −137ef | −165e | <0.0001 |
| SC8 | 55 | 1.43 | 1.17 | −12a | −131d | −210e | −225e | −38b | −99c | −229e | −285f | <0.0001 |
| SC9 | 55 | 2.20 | 2.20 | −12a | −203d | −318e | −405f | −38b | −171c | −337e | −465g | <0.0001 |

[†] The letters represent harvest system, the first number is kg of N ha$^{-1}$ and the second number is kg of $K_2O$ ha$^{-1}$

[‡] $P$ values are based on Fisher's protected $F$ tests

[§] Means within a row followed by same letter are not significantly different based on an LSD test ($P<0.05$)

The letters *SC* represent price scenario (i.e., \$1.43 and \$1.17 kg$^{-1}$, respectively), the farm level breakeven prices of feedstock for the SW/0/0 and SW/135/67 systems were equal to \$55.9 and \$66.8 Mg$^{-1}$, respectively. It is noteworthy to point out that the literature reports biorefinery breakeven prices for switchgrass feedstock (and other sources of cellulosic feedstock) range between \$33 and \$68 Mg$^{-1}$ for different conversion technologies [37–44]. This range in biorefinery willingness to pay for feedstock is much lower than what will be required by farmers to grow switchgrass as a dedicated feedstock crop on their farms.

When a feedstock price of \$110 Mg$^{-1}$ and the relatively low price of \$0.77 kg$^{-1}$ for N and K were assumed in the analysis, the SW/135/67 production system was found to be statistically more profitable than the SW/0/0 system. At these prices, the value of the additional yield obtained with the SW/135/67 system was greater than the additional harvest costs and the costs associated with the 135 and 67 kg ha$^{-1}$ applications of N and K fertilizers. However, when the price of feedstock was \$110 Mg$^{-1}$ and the base–case prices for N and K (i.e., \$1.43 and \$1.17, respectively) were assumed, the net returns for the SW/0/0 and SW/135/67 systems were statistically breakeven with each other. Once again, we point out that the ability of a large-scale biorefinery to pay \$110 Mg$^{-1}$ for switchgrass feedstock does not appear, based on the literature, to be feasible, given the existing technologies available for converting switchgrass biomass into ethanol and other forms of biofuels.

## Conclusion

Limited economic information is available regarding the management of harvest timing and fertilizer applications for switchgrass feedstock produced in K-deficient soil in the southern Great Plains. Data collected from a 4-year agronomic field study were used to evaluate the economics of eight alternative switchgrass harvest time, N, and K fertilizer production systems. Results reveal that a production system that included a two-cut (summer and winter) harvest system and utilizes fertilizer applications of 135 and 67 kg ha$^{-1}$ of N and K, respectively, produced the greatest feedstock yield. However, this system was not competitive economically with a two-cut (summer and winter) harvest system without applications of N and K; the benefits from the additional yield were not enough to cover the expenses associated with the N and K fertilizer, their application costs, and the additional harvest costs. Furthermore, the results of this study indicate that the most economical farmer-based harvest timing and nutrient application system for producing switchgrass in K-deficient soil is largely dependent on the price producers can expect to receive for their feedstock. For a feedstock price equal to \$55 Mg$^{-1}$, net returns for all eight systems were negative. At this price, producers will have no interest in producing switchgrass as a dedicated energy crop on their K-deficient soil in the southern Great Plains.

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## References

1. Haque M, Biermacher JT, Kering MK, Guretzky JA (2013) Economics of alternative fertilizer supply systems for switchgrass produced in phosphorus-deficient soils for bioenergy feedstock. Bioenerg Res 6:351–357
2. Zhang H, Raun B (2008) Oklahoma homeowner's handbook for soil and nutrient management. 2nd edn. E-1003, Oklahoma Cooperative Extension Service, Oklahoma State University, Stillwater, Oklahoma
3. Haque M, Epplin FM, Taliaferro CM (2009) Nitrogen and harvest frequency effect on yield and cost of four perennial grasses. Agron J 10:1463–1469
4. Aravindhakshan SC, Epplin FM, Taliaferro CM (2011) Switchgrass, bermudagrass, flaccidgrass, and lovegrass biomass yield response to nitrogen for single and double harvest. Biomass Bioenergy 35:308–319
5. Boyer CN, Tyler DD, Roberts RK, English BC, Larson JA (2012) Switchgrass yield response functions and profit-maximizing nitrogen rates on four landscapes in Tennessee. Agron J 104(6):1579–1588
6. Muir JP, Sanderson MA, Ocumpaugh WR, Jones RM, Reed RL (2001) Biomass production of 'Alamo' switchgrass in response to nitrogen, phosphorus, and row spacing. Agron J 93:896–901
7. Kering MK, Biermacher JT, Butler TJ, Mosali J, Guretzky JA (2012) Biomass yield and nutrient responses of switchgrass to phosphorus application. Bioenerg Res 5(1):71–78
8. Marschner P (2011) Mineral nutrition of higher plants, 3rd edn. Academic, London, pp 135–178
9. Kering MK, Twain TJ, Biermacher JT, Mosali J, Guretzky JA (2012) Effect of potassium and nitrogen fertilizer on switchgrass productivity and nutrient removal rates under two harvest systems on a low potassium soil. Bioenerg Res. doi:10.1007/s12155-012-9261-8
10. Potash & Phosphate Institute. PPI. (2006) Role of potassium in crop establishment. GRI-BRIEFS Agronomic news items, no. 2. Internet site: http://www.ipni.net/ppiweb/agbrief.nsf/5a4b8be72a35cd46852568d9001a18da/098d1384ac67e0d08525714700579b6a!OpenDocument. Accessed 23 April 2013
11. Friedrich JW, Smith D, Schrader LE (1977) Herbage yield and chemical composition of switchgrass as affected by N, S, and K fertilization. Agron J 69:30–32
12. Smith D (1979) Fertilization of switchgrass in the greenhouse with various levels of nitrogen and potassium. Agron J 71:149–150
13. Taylor RW, Allinson DW (1982) Response of three warm-season grasses to varying fertility levels on five soils. Can J Plant Sci 62:657–665
14. Guretzky J, Biermacher JT, Cook B, Kering M, Mosali J (2011) Switchgrass for forage and bioenergy: harvest and nitrogen rate effects on biomass yields and nutrient composition. Plant Soil 339(1–2):69–81
15. McLaughlin MR, Fairbrother TE, Rowe DE (2004) Nutrient uptake by warm-season perennial grasses in a swine effluent spray field. Agron J 96:484–493
16. Thomason WE, Raun WR, Johnson GV, Taliaferro CM, Freeman KW, Wynn KJ, Mullen RW (2004) Switchgrass response to harvest frequency and time and rate of applied nitrogen. J Plant Nutr 27:1199–1226

17. Sanderson MA, Read JC, Reed RL (1999) Harvest management of switchgrass for biomass feedstock and forage production. Agron J 91:5–10
18. Reynolds JH, Walker CL, Kirchner MJ (2000) Nitrogen removal in switchgrass biomass under two harvest systems. Biomass Bioenerg 19:281–286
19. Zhang H, Raun B (2006) Oklahoma soil fertility handbook. 6th edn. Oklahoma Cooperative Extension Service, Oklahoma State University, Stillwater, Oklahoma
20. Lawrence J, Cherney J, Barney P, Ketterings Q (2006) Establishment and management of switchgrass. Cornell University Cooperative Extension. Fact sheet 20. http://forages.org/bioenergy/downloads/Switchgrassfactsheet20.pdf. Accessed 26 January 2010
21. American Agricultural Economics Association. AAEA. (2000) Commodity costs and returns estimation handbook. A report of the AAEA task force on commodity costs and returns. Ames, Iowa, USA
22. Farm Credit (2010) Farm Credit System Bank Interest Rates for 2010 and 2011. Rev. Rul. 2011–17. Internet site: http://www.fs.fed.us/spf/coop/library/2010_2011%20bank%20rates.pdf. Accessed 20 July 2013
23. Doye D, Sahs R (2012) Oklahoma farm and ranch custom rates, 2011–2012. Oklahoma State University, Oklahoma Cooperative Extension Service, CR-205 (1111 Rev)
24. Mooney DF, Roberts RK, English BC, Tyler DD, Larson JA (2008) Switchgrass production in marginal environments: A comparative economic analysis across four West Tennessee landscapes. Paper presented at American Agricultural Economics Association Annual Meeting, July 25–27, Orlando, FL
25. Epplin FM, Clark CD, Roberts RK, Hwang S (2007) Challenges to the development of a dedicated energy crop. Am J Agric Econ 89(5):1296–1302
26. Littell RC, Milliken GA, Stroup WW, Wolfinger RD (1996) SAS System for Mixed Models. SAS Inst, Cary, NC
27. SAS Institute (2008) SAS/STAT. SAS System for Windows. v. 9.2. SAS Inst, Cary, NC
28. Biermacher JT, Brorsen BW, Epplin FM, Solie JB, Raun WR (2009) The economic potential of precision nitrogen application with wheat based on plant sensing. Agric Econ 40:397–407
29. Ramirez OA (1997) Estimation and use of multivariate parametric model for simulating heteroscedastic, correlated, non-normal random variables: the case of Corn Belt corn, soybean, and wheat yields. Am J Agric Econ 79:291–305
30. Just RE, Weninger Q (1999) Are crop yields normally distributed? Am J Agric Econ 81(2):287–304
31. Kapiamba LF (2005) Modeling heteroskedasticity of crop yield distributions: implications for normality. AAEA Annual Meetings, Providence, Rhode Island, July 24–27
32. D'Agostino RB, Belanger A, D'Agostino RB Jr (1990) A suggestion for using powerful and informative tests of normality. Amer Statist 44(4):316–321
33. Boyer CN, Brorsen W, Solie JB, Raun WR (2011) Profitability of variable rate nitrogen application in wheat production. Precis Agric 12:473–487. doi:10.1007/s11119-010-9190-5
34. Greene WH (2008) Econometric analysis. Hypothesis and specification tests and fit measures, 6th edn. Pearson Education, Inc, Upper Saddle River, New Jersey, pp 498–500
35. Slaton NA, Massey CG, DeLong RE, Haller B, Gordon B (2011) 'Midland 99' bermudagrass forage yield response to phosphorus and potassium fertilization. Wayne E. Sabbe Arkansas Soil Fertility Studies
36. Haque M, Biermacher JT, Kering MK, Guretzky JA (2012) Does nutrient mining affect the choice of harvest system and nutrient management strategy for producing switchgrass biomass? Selected paper presented at the Agricultural and Applied Economics Association Annual Meetings, Seattle, Washington, 12–14 August
37. Haque M, Epplin FM (2012) Cost to produce switchgrass and cost to produce ethanol from switchgrass for several levels of biorefinery investment cost and biomass to ethanol conversion rates. Biomass Bioenergy 46:517–530
38. Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, et al. (2002) Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Golden, CO: National Renewable Energy Laboratory; Report No. NREL/TP-510e32438
39. Eggeman T, Elander RT (2005) Process and economic analysis of pretreatment technologies. Bioresource Technol 96:2019–2025
40. Nguyen QA, Saddler JN (1991) An integrated model for the technical and economic evaluation of an enzymatic biomass conversion process. Bioresource Technol 35:275–282
41. Wingren A, Galbe M, Zacchi G (2003) Techno-economic evaluation of producing ethanol from softwood: comparison of SSF and SHF and identification of bottlenecks. Review. Biotechnol Prog 19:1109–1117
42. Sendich EN, Laser M, Kim S, Alizadeh H, Laureano-Perez L, Dale B, Lynd L (2008) Recent process improvements for the ammonia fiber expansion (AFEX) process and resulting reductions in minimum ethanol selling price. Bioresource Technol 99:8429–8435
43. Wu J, Sperow M, Wang J (2010) Economic feasibility of a woody biomass-based ethanol plant in central Appalachia. J Agri Resour Econ 35:522–544
44. Humbird D, Davis R, Tao L, Kinchin C, Hsu D, Aden A, Schoen P, Lukas J, Olthof B, Worley M, Sexton D, Dudgeon D (2011). Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: dilute-acid pretreatment and enzymatic hydrolysis of corn stover. U.S. Department of Energy National Renewable Energy Laboratory, Golden, Colorado, Technical Report NREL/TP-5100-47764