Fertilizer Recommendations for Switchgrass: Quantifying Economic Effects on Quality and Yield


ABSTRACT

Switchgrass (*Panicum virgatum* L.) is a native, perennial warm-season grass suited for biomass production for renewable fuels and also fodder on marginal soils. To develop fertilizer recommendations, yield responses to and nutrient removal in harvest biomass associated with five levels of macronutrients of N, P, and K on Leadville silt loam (fine-silty, siliceous, semiactive, thermic Typic Fragiudults) with a fragipan at 14 to 97 cm at a mid-southern US location were examined. Feed quality was assessed using crude protein (CP) and total digestible nutrient (TDN) concentration to assess feasibility in beef cow (*Bos taurus*) rations. Nitrogen affected economic performance to a larger extent than P and K. Profit-maximizing K use rivaled that of N use, whereas P use was lower and thereby limited sustainable poultry litter application. Hay ranged between 7 and 9% CP and 51% ± 0.5% TDN in response to harvest time and nutrient application rate. Cattle producers would find such hay suitable for maintaining dry cows without need for supplemental feed. Profitability of hay production and fertilizer recommendations varied largely with changes in switchgrass price and fertilizer cost. As such, a supplemental spreadsheet tool was developed for research outreach purposes to provide output price- and input cost-specific fertilizer recommendations for switchgrass hay with attendant quality impacts. Overall, breakeven prices were lower using inexpensive litter in comparison with synthetic fertilizers and ranged from approximately US$40 to US$60 Mg⁻¹ in this study. Therefore, switchgrass hay compared favorably in cost to traditional hay averaging US$126 Mg⁻¹ over the study period.

Core Ideas

- Fertilizer recommendations for switchgrass depend on its price and fertilizer cost.
- Different fertilizer rates affect yield and hay quality for first and second cuts.
- Substituting poultry litter for fertilizer affects breakeven, yield, and quality.
- Switchgrass hay can compete with traditional hay in cattle rations.

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Abbreviations: CP, crude protein; TDN, total digestible nutrient; ENCAP, Energy Crop Analysis and Planning.
litter offers the potential to recycle nutrients as some nutrients contained in bird feed are captured in poultry litter that is subsequently spread on fields to grow more feed, although not necessarily to feed birds. A complication with manure application is the potential to apply excess nutrients because manures may have a different nutrient make-up than the nutrient needs of the crop fertilized. Excess application of N, P, or both can then create environmental costs by way of nutrient run-off and leaching (DeLaune et al., 2004).

With the most growth-limiting nutrient for switchgrass being N (Brejda, 2000; Muir et al., 2001; Vogel et al., 2002), nutrient application levels to achieve peak yield have been estimated near 170 kg ha\(^{-1}\) in single-cut systems. Alternatively, N needs for each Mg ha\(^{-1}\) range between 10 and 12 kg N ha\(^{-1}\) and depend on soil texture and weather conditions. With two harvests per year, however, N needs are expected to be higher, as early harvest leads to much higher nutrient removal than in single-cut systems for harvest of biomass for biofuels that ideally occurs post-senescence (Gouzaye et al., 2014; Cahill et al., 2014; Ashworth et al., 2017). On the other hand, switchgrass demonstrates very high P use efficiency (Brejda, 2000; Muir et al., 2001; Cahill et al., 2014; Gouzaye et al., 2014). Application levels less than 35 kg ha\(^{-1}\) are common in the literature, but again, two cuttings may well increase use of this nutrient. Finally, K is an essential macronutrient, with forage studies typically recognizing the need to apply N and K at similar levels (Slaton et al., 2011).

However, yield response to K in switchgrass with multiple cuts may very well reach levels that rival its importance with N fertilizer, as the interaction between N and K fertilizer application is not well understood (Kering et al., 2013a) and may be synergistic, suggesting higher levels of both N and K may lead to yield improvement. Nonetheless, these synergies may be difficult to separate (Kering et al., 2013a).

The purpose of this work, therefore, was to (i) estimate switchgrass yield response to nutrient input application when harvested twice per year (early June and late July); (ii) determine profit-maximizing fertilizer recommendations based on the prices of switchgrass hay and fertilizer/manure inputs (Samson et al., 2005; Boyer et al., 2012; Cahill et al., 2014); (iii) estimate the quality of hay as a result of fertilizer use because quality impacts beef cattle feed rations (Kering et al., 2013b; Obour et al., 2017); and (iv) calculate break-even prices for switchgrass hay to determine how conventional hay profitability compares with switchgrass hay profitability.

**MATERIALS AND METHODS**

**Site Description**

The yield response study for N, P, and K was conducted at the Natural Research Conservation Service, Plant Materials Center in Booneville, AR (35.08°N, –93.55°W), in the karst topography region on Leadvale silt loam (fine-silty, siliceous, semiactive, thermic Typic Fragiaudults). A fragipan at depths ranging from 14 to 97 cm restricted water movement and root development (NRCS Soil Survey, 2003), and hence, the site is considered representative of marginal quality land where switchgrass production would not compete with food, feed, and fiber production (McKenna and Wolf, 1990). Initial soil tests performed in the spring prior to the experiment showed low P and K concentrations that were considered low for native warm-season grass pasture or hay crops.

**Experimental Design and Treatment Applications**

This experiment utilized a two-factor, factorially arranged, randomized complete block design with four replications for each macro nutrient yield response. The first factor, fertility treatment, was applied annually with dependent variables (yield and forage quality) collected twice annually with harvest time (June or July) as the second factor. Nitrogen, P, and K were applied at five different rates each (Table 1) on switchgrass cv. Alamo stands established in the spring of 2007 on 2.4 × 4.6 m plots with 18-cm row spacing. Given low soil P and K levels, application levels of P and K, when not varied, were high to assure that switchgrass nutrient deficiency did not affect yield potential. Nitrogen application was held near the middle of the application range applied for the P and K response trials so as not to mask potential yield responses of P and K by applying yield-maximizing levels of N. Fertilizer was split-applied with the first application occurring in mid-April and a second application in early June, immediately after the first harvest. Nitrogen, P, and K was applied in the form of ammonium nitrate, triple superphosphate [Ca(H\(_2\)PO\(_4\))\(_2\) H\(_2\)O], and potash (K\(_2\)O), respectively. Note that control plots with no nutrient applications of any kind were not analyzed, and hence, zero fertilizer application rates were analyzed in conjunction with constant rates of application of the other two macronutrients (Table 1). Chemical weed control was not required because the switchgrass stand was dense enough to limit invasive species growth.

**Data Collection**

Yield data for each harvest were collected from 2014 to 2016 with first harvest dates of 3 June 2014, 8 June 2015, and 9 June 2016, and second harvest dates of 29 July 2014 and 2015 and 26 July in 2016. Plots were harvested with a Carter (Carter Mfg Co.) forage harvester (Brookston, IN) at 15.2-cm stubble height. Grab samples of biomass (1–2 kg) were collected from all plots at harvest, weighed, and dried at 55°C in a batch oven (Wisconsin Oven Corporation, East Troy, WI) for 48 to 72 h to record moisture content and convert observed yield to dry matter yield in kg ha\(^{-1}\). Samples were subsequently ground to 2-mm particle size or less using a Wiley mill (Thomas Scientific, Swedesboro, NJ) to assess N, P, and K concentration in the biomass and thereby calculate of N, P, and K removal per unit

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**Table 1. Nutrient application rates, Booneville, AR, 2014–2016.†**

<table>
<thead>
<tr>
<th>Study/nutrient</th>
<th>N response plots</th>
<th>P response plots</th>
<th>K response plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nutrient application rate, kg ha(^{-1})</td>
<td>0, 84, 168, 252, and 336</td>
<td>224</td>
<td>0, 28, 56, 112, and 224</td>
</tr>
<tr>
<td></td>
<td>224</td>
<td>224</td>
<td>0, 135, 269, 404, and 426</td>
</tr>
</tbody>
</table>

† Because soil-extractable S, an essential plant micronutrient, was at low levels, all plots received annual supplemental S fertilizer at the rate of 74 kg ha\(^{-1}\).

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**Note:**

- **Table 1. Nutrient application rates, Booneville, AR, 2014–2016.†**
  - **Study/nutrient:**
    - N response plots: 0, 84, 168, 252, and 336
    - P response plots: 224
    - K response plots: 224
  - **Nutrient application rate, kg ha\(^{-1}\):**
    - N: 0, 84, 168, 252, and 336
    - P: 0, 28, 56, 112, and 224
    - K: 0, 135, 269, 404, and 426
  - † Because soil-extractable S, an essential plant micronutrient, was at low levels, all plots received annual supplemental S fertilizer at the rate of 74 kg ha\(^{-1}\).

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**MATLAB Code:**

```matlab
% Code for analysis of switchgrass nutrient application rates
% Booneville, AR, 2014–2016

% Table 1: Nutrient application rates, Booneville, AR, 2014–2016

% Study/nutrient
% N response plots: 0, 84, 168, 252, and 336
% P response plots: 224
% K response plots: 224

% Nutrient application rate, kg ha\(^{-1}\):
% N: 0, 84, 168, 252, and 336
% P: 0, 28, 56, 112, and 224
% K: 0, 135, 269, 404, and 426

% Because soil-extractable S, an essential plant micronutrient, was at low levels, all plots received annual supplemental S fertilizer at the rate of 74 kg ha\(^{-1}\).
Profit-Maximizing Nitrogen Application Rate

To estimate the effect of nutrient application rate on yield, generalized least squares in EViews v9 (Lilien et al., 2015) was used on panel data of first and second switchgrass harvests with year as a random effect:

\[ Y_{ir} = \alpha_{0i} + \alpha_{1i} N_i + \alpha_{2i} N_i^2 + \psi_i + \varepsilon_{ir} \]  
(\( i = 1, 2; t = 1, 2, 3; s = 1, 2, 3, 4, 5 \))

where \( Y_{ir} \) in kg ha^{-1} is the yield per harvest period \( i \), where \( i = 1 \) is the June harvest and \( i = 2 \) is the July harvest, \( t \) represents the production year, \( N_i \) represents one of five N application rates, \( \alpha_{0i} \) are the constant terms for each harvest, \( \alpha_{1i} \) and \( \alpha_{2i} \) are the linear and nonlinear N response coefficients that vary by harvest period, \( \psi_i \) are the random year effects that vary by harvest period, and \( \varepsilon_{ir} \) is the error term for each yield observation. In addition to the quadratic functional form shown in Eq. [1], square root, transcendental, and Mitscherlich-Baule functional forms were also estimated to compare goodness of fit on the basis of adjusted \( R^2 \) and number of individual \( t \) statistics that added explanatory power (| \( t \)-stat | > 1.0) for N. A Hausman test indicated that production year could be treated as a random effect rather than a fixed effect (Green, 2008). Further, estimating first and second harvest yields, separately, allowed determination of full year yield estimates by summing predicted yields, \( \bar{Y}_{1ir} \) and \( \bar{Y}_{2ir} \). The yield response to N application (Eq. [1]) thus provides an N application recommendation that accounts for PR and KR as well as their cost.

Profit-maximizing N application rate was determined as a function of its cost, \( n \), and the price of switchgrass \( P_{sg} \) as follows:

\[ \left[ \alpha_{1i} + \alpha_{12} + 2(\alpha_{21} + \alpha_{22}) N \right] \times P_{sg} = n \]  
[2]

where the left hand side of the equation represents the value of an added kg of N applied, the partial derivative of Eq. [1] with respect to N times the price for switchgrass, and the right hand side represents the cost of that added unit of N. The optimal N application rate, \( N^* \), meets profit-maximizing conditions:

\[ N^* = \frac{n}{P_{sg}} = \frac{-\alpha_{1i} - \alpha_{12}}{2(\alpha_{21} + \alpha_{22})} \]  
[3]

and can be estimated by replacing the unknown parameters with their estimates for given \( n \) and \( P_{sg} \). Note that \( N^* \) does not vary by year but does vary with changes in the cost of fertilizer, \( n \), and the price of switchgrass, \( P_{sg} \).

A complicating factor, however, is that varying levels of N application affect not only N removal in the harvests but also P and K concentration in the harvested biomass. Hence, N, P, and K removal were estimated as follows:

\[ NR_{its} = \beta_{0i} + \beta_{1i} N_i + \tau_{it} + \eta_{its} \]  
\( (i = 1, 2; t = 1, 2, 3; s = 1, 2, 3, 4, 5) \)  
[4]

\[ KR_{its} = \gamma_{0i} + \gamma_{1i} NR_{its} + \phi_{it} + \eta_{its} \]  
\( (i = 1, 2; t = 1, 2, 3; s = 1, 2, 3, 4, 5) \)  
[5]

\[ PR_{its} = \delta_{0i} + \delta_{1i} NR_{its} + \psi_{it} + \eta_{its} \]  
\( (i = 1, 2; t = 1, 2, 3; s = 1, 2, 3, 4, 5) \)  
[6]

where \( NR, KR, \) and \( PR \) are the amounts of N, P, and K removed in the harvested biomass in kg ha^{-1} at each harvest; \( t \) represents the production year; \( s \) is one of five nutrient application rates; \( \beta, \gamma, \) and \( \phi, \delta, \) and \( \tau, \eta, \phi, \delta, \) and \( \eta \) are constant terms and coefficient estimates by harvest period; \( N_i \) is the amount of N applied; \( \alpha_{0i} \) are random year effects and \( \alpha_{1i}, \alpha_{2i} \) are random year effects; \( \gamma_{0i}, \gamma_{1i}, \) and \( \gamma_{1s} \) are error terms for each nutrient removal observation. Since \( NR, KR, \) and \( PR \) are highly correlated, \( NR \) proved a better predictor than \( N_i \) applied in Eq. [5] and [6].

The marginal cost of N applied per unit area thus changes from its cost, \( n \), to the amount of N as a result of applied N and attendant nutrient needs of PR and KR as follows:

\[ n' = \beta_{11} (n + \gamma_{1k} k + \delta_{1p} p) + \beta_{12} (n + \gamma_{1k} k + \delta_{1p} p) \]  
[7]

where \( \beta_{11}, \gamma_{1k}, \) and \( \delta_{1p} \) are marginal effects of applying N on nutrient removal of N, P, and K specific to each harvest \( i \) and \( k \), and \( p \) are prices paid for fertilizers adjusted for N, P, and K content in commercial fertilizers of ammonium nitrate, triple super phosphate, and potash, respectively. Substituting \( n' \) for \( n \) in Eq. [3] thus provides an N application recommendation that accounts for PR and KR as well as their cost.

Optimum switchgrass hay profit with dual harvest could then be estimated as:

\[ \pi = Y \times (P_{sg} - b) - N^* \times n - KR \times k - PR \times p - f \]  
[8]

where \( \pi \) is the estimated profitability expressed in $ ha^{-1}, Y \) is the estimated sum of yields for both harvests when \( N^* \) of nitrogen is applied, \( b \) is a yield-independent cost of harvesting biomass in $ ha^{-1} set at $25 Mg^{-1} as a default charge for fuel, labor, and equipment costs, and \( f \) is the cost to apply fertilizer twice per year set at $15 ha^{-1} to cover fuel, labor, and equipment charges. Other variables are as described above. Note that \( N^* \) would be replaced by \( NR \) if \( N^* \) was below \( NR \) such that \( NR - N^* \) would be applied with the second fertilizer application to make the production system sustainable from year to year. This condition is expected to occur rarely and is directly related to a low switchgrass price when profitability estimates are low or negative and thereby an occurrence that would not hold in the long run as producers would not plan to grow switchgrass for hay if not profitable. Should \( N^* \) be larger than \( NR \), nutrient leaching or N buildup in the soil would occur. This situation could arise with low fertilizer prices and/or high switchgrass prices.

The profitability equation is used to perform a break-even analysis to determine the minimum switchgrass price a
Table 2. Inflation-adjusted hay and fertilizer prices, 2005–2014, in 2017 dollars.

<table>
<thead>
<tr>
<th>Year</th>
<th>Hay†</th>
<th>Ammonium nitrate (34–0–0)</th>
<th>Triple super phosphate (0–45–0)</th>
<th>Potash (0–0–60)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>0.127</td>
<td>1.294</td>
<td>2.252</td>
<td>0.738</td>
</tr>
<tr>
<td>2006</td>
<td>0.135</td>
<td>1.513</td>
<td>2.276</td>
<td>0.767</td>
</tr>
<tr>
<td>2007</td>
<td>0.141</td>
<td>1.288</td>
<td>2.395</td>
<td>0.642</td>
</tr>
<tr>
<td>2008</td>
<td>0.126</td>
<td>0.944</td>
<td>2.523</td>
<td>0.708</td>
</tr>
<tr>
<td>2009</td>
<td>0.140</td>
<td>1.156</td>
<td>2.866</td>
<td>1.530</td>
</tr>
<tr>
<td>2010</td>
<td>0.122</td>
<td>1.146</td>
<td>2.481</td>
<td>1.000</td>
</tr>
<tr>
<td>2011</td>
<td>0.115</td>
<td>1.059</td>
<td>2.379</td>
<td>0.904</td>
</tr>
<tr>
<td>2012</td>
<td>0.139</td>
<td>1.252</td>
<td>2.702</td>
<td>0.986</td>
</tr>
<tr>
<td>2013</td>
<td>0.154</td>
<td>1.244</td>
<td>2.725</td>
<td>0.925</td>
</tr>
<tr>
<td>2014</td>
<td>0.131</td>
<td>1.310</td>
<td>2.470</td>
<td>0.956</td>
</tr>
<tr>
<td>Avg.</td>
<td>0.133</td>
<td>1.220</td>
<td>2.507</td>
<td>0.916</td>
</tr>
<tr>
<td>Min.§</td>
<td>0.154</td>
<td>1.513</td>
<td>2.866</td>
<td>1.530</td>
</tr>
<tr>
<td>Min.¶</td>
<td>0.115</td>
<td>0.944</td>
<td>2.252</td>
<td>0.642</td>
</tr>
</tbody>
</table>

‡ Fertilizer prices as available at NASS (2017c, 2017d, 2017e) for 2005–2014. Prices are deflated using the 2011 U.S. fertilizer prices paid index and converted to 2017 dollars (NASS, 2017f). Nutrient prices are further converted to $ kg⁻¹ of actual nutrient. For ammonium nitrate, triple superphosphate, and potash, 34 kg N, 20 kg P, and 50 kg K 100 kg⁻¹ fertilizer are used, respectively.
§ The maximum price year for fertilizers was 2009 using the weighted average of fertilizers with twice the weight on N and K compared with P. Maximum hay price occurred in 2013.
¶ The minimum price year for fertilizers was 2008 using the weighted average of fertilizers with twice the weight on N and K compared with P. Minimum hay price also occurred in 2011.

Sensitivity Analyses

The above model allows for different estimates of profit-maximizing N application rates, attendant profitability, and quality estimates of hay that are subject to varying input and output price levels. As such, producers need answers about fertilizer recommendations as they vary with changes in $P^*_h$ or the price of switchgrass hay and fertilizer prices as observed over the last 10 yr as shown in Table 2. Changes in these prices also affect the breakeven price of switchgrass where revenue from the sale of hay is equal to costs incurred during its production. These breakeven prices are helpful for comparison to prices of conventional hay of similar quality.

Further, poultry litter is often a less expensive source of fertility than synthetic fertilizer on hay fields in the production region analyzed. Poultry litter, which can vary in nutrient composition, leads to modified prices for $n, p, k$ and $f$ using methods as described in Cahill et al. (2014) and Lindsay et al. (2018). It is unlikely that poultry litter alone can meet nutrient needs of switchgrass as the nutrient make up of poultry litter does not match the nutrient needs of switchgrass, and hence, supplementation with synthetic fertilizers is needed to avoid over application of nutrients as described above. Further, poultry litter contains both organic and inorganic forms of nutrients where the latter is readily available for plant uptake and use, whereas organic forms of N are less immediately available and need to mineralize before becoming useful to the plant. The mineralization rate increases with humid and warm conditions typically prevalent in the production region analyzed and hence this study assumes all forms of N will be available to established switchgrass plants in the year of application (Moore and Edwards, 2005).

In sum, sensitivity analyses with respect to fertilizer type (poultry litter of varying quality or synthetic fertilizers of varying nutrient composition), cost for said nutrients, and switchgrass price are large in number and tedious to perform. Although a table of several outprice and input cost changes is prepared within, the reader is directed to the supplemental Excel™ file to experiment with changes to switchgrass price, fertilizer cost, fertilizer type, and harvest cost parameters.

Yield Response to Other Nutrients

Although N is typically deemed the dominant factor for determining yield in switchgrass (Guretzky et al., 2011; Gouzaye et al., 2014; Cahill et al., 2014; Ashworth et al., 2017; Lindsay et al., 2018), yield response to P and K was estimated using a similar approach as the one for the yield response to N (Eq. [1]), except that yield for both harvests was chosen as the dependent variable. These response functions were not estimated to develop economically optimal fertilizer recommendations, but their shapes reveal how yield responded to alternative rates of K and P when the other nutrients were non-yield limiting. The K and P yield response functions were specified as follows:

\[
CP_{it} = \lambda_{0i} + \lambda_{1i} Y_{its} + \lambda_{2i} N_s + \delta_{it} + \mu_{its}, \quad (i = 1, 2, 3; t = 1, 2, 3; s = 1, 2, 3, 4, 5) \quad [9] 
\]

\[
TDN_{its} = \rho_{0i} + \rho_{1i} Y_{its} + \rho_{2i} N_s + \beta_{it} + \sigma_{its}, \quad (i = 1, 2; t = 1, 2; 3; s = 1, 2, 3, 4, 5) \quad [10] 
\]

where CP_{it} and TDN_{its} are % dry matter nutrient concentrations of the harvested switchgrass for harvest period $i$, $t$ represents the production year, $s$ is one of five nutrient application rates and attendant yield, $\lambda_i$ and $\rho_i$ are each constant term and coefficient estimates for yield and N application per harvest period, $\delta_{it}$ and $\beta_{it}$ are random year effects, and $\mu_{its}$ and $\sigma_{its}$ are error terms for each observation.

Note that Eq. [1], [4–6], and [9–10] were estimated using generalized least squares on panel data with year treated as a random observation.
\[
Y_{ts} = \nu_0 + \nu_1 K_s + \nu_2 \frac{K_s^2}{s} + \omega_t + \xi_{ts} \\
(t = 1, 2, 3; s = 1, 2, 3, 4, 5) [11]
\]

\[
Y_{ts} = \kappa_0 + \kappa_1 P_s + \kappa_2 \sqrt{P_s} + \varsigma_t + \iota_{ts} \\
(t = 1, 2, 3; s = 1, 2, 3, 4, 5) [12]
\]

where \(K_s\) and \(P_s\) were \(K\) and \(P\) application rates in kg ha\(^{-1}\) (Table 1), \(\nu\) and \(\kappa\) are each constant terms and coefficient estimates, \(\omega\) and \(\varsigma\) are random year effects, and \(\xi\) and \(\iota\) are error terms for each observation. Random year effects and error terms were again assumed identically and independently distributed. Yield maximizing input rates were also calculated where the partial derivative of yield with respect to respective nutrient inputs was set to zero and solved for the corresponding levels of input use.

**RESULTS**

Estimated parameters for Eq. [1], [4–6], and [9–12] showed appropriate signs and statistical significance (Table 3). Further, most of the variation in the dependent variables was explained by changes in the explanatory variables as evidenced by the high adjusted \(R^2\) values. An exception was the relatively poor explanatory power of the \(P\) and \(K\) yield curves (Eq. [11] and [12]), as well as the estimation of TDN as a function of yield and \(N\) application (Eq. [10]). These latter equations, however, played a negligible role for the purpose of estimating profit-maximizing nutrient application rates for harvesting switchgrass as hay. Hence, using the above system of equations to estimate yield response, nutrient replacement cost, and attendant estimates of profitability was deemed appropriate.

![Fig. 1. Estimated yield response to \(N\), \(P\), and \(K\) fertilizer with yield-maximizing \(N\), \(P\), and \(K\) rates and profit-maximizing \(N\) rate and yields using a switchgrass hay price of $65 Mg^{-1} and average synthetic fertilizer prices, Booneville, AR, 2014–2016. See Table 2 for a history of fertilizer and hay prices.](image)

As shown in Fig. 1, the yield response functions to \(P\) and \(K\) are much flatter than the yield response function to \(N\). This supports findings of Guretzky et al. (2011), Kering et al. (2013a), and Ashworth et al. (2017) in that \(N\) is the major yield driver with \(P\) and \(K\) playing a supporting role. Further, the shape of...
### Table 4. Profit-maximizing annual estimated fertilizer use, yield, N-, P-, and K- removal in harvested biomass, hay quality, profitability†, and switchgrass breakeven price as they vary by poultry litter use and synthetic fertilizer prices, Booneville, AR, 2014–2016 with switchgrass price at $65 Mg–1.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Est. yield, Mg ha–1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>17.0</td>
<td>15.7</td>
<td>13.8</td>
<td></td>
<td>18.4</td>
<td>18.0</td>
<td>17.2</td>
</tr>
<tr>
<td>Syn. N use, kg ha–1</td>
<td>223</td>
<td>186</td>
<td>142</td>
<td>56</td>
<td>49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syn. P use, kg ha–1</td>
<td>29</td>
<td>26</td>
<td>23</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Syn. K use, kg ha–1</td>
<td>221</td>
<td>198</td>
<td>169</td>
<td>173</td>
<td>166</td>
<td>151</td>
<td></td>
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<tr>
<td>Litter applied, Mg ha–1</td>
<td></td>
<td></td>
<td></td>
<td>5.5</td>
<td>5.3</td>
<td>4.9</td>
<td></td>
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<tr>
<td>N from litter, kg ha–1</td>
<td></td>
<td></td>
<td></td>
<td>221</td>
<td>213</td>
<td>197</td>
<td></td>
</tr>
<tr>
<td>P from litter, kg ha–1</td>
<td></td>
<td></td>
<td></td>
<td>33</td>
<td>32</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>K from litter, kg ha–1</td>
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<td></td>
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<td>83</td>
<td>80</td>
<td>74</td>
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</tr>
<tr>
<td>N removed, kg ha–1</td>
<td>194</td>
<td>171</td>
<td>142</td>
<td>227</td>
<td>218</td>
<td>197</td>
<td></td>
</tr>
<tr>
<td>P removed, kg ha–1</td>
<td>29</td>
<td>26</td>
<td>23</td>
<td>256</td>
<td>246</td>
<td>225</td>
<td></td>
</tr>
<tr>
<td>K removed, kg ha–1</td>
<td>221</td>
<td>198</td>
<td>169</td>
<td>256</td>
<td>246</td>
<td>225</td>
<td></td>
</tr>
<tr>
<td>CP, % mass basis</td>
<td>7.41</td>
<td>7.11</td>
<td>6.79</td>
<td>7.93</td>
<td>7.77</td>
<td>7.47</td>
<td></td>
</tr>
<tr>
<td>TDN, % mass basis</td>
<td>51.27</td>
<td>51.30</td>
<td>51.45</td>
<td>51.39</td>
<td>51.34</td>
<td>51.27</td>
<td></td>
</tr>
<tr>
<td>Profit†, $ ha–1</td>
<td>225</td>
<td>140</td>
<td>48</td>
<td>392</td>
<td>349</td>
<td>269</td>
<td></td>
</tr>
<tr>
<td>Breakeven switchgrass Price¶, $ Mg–1</td>
<td>48.61</td>
<td>53.92</td>
<td>61.38</td>
<td>38.47</td>
<td>39.65</td>
<td>44.71</td>
<td></td>
</tr>
</tbody>
</table>

† Profitability is calculated as specified in Eq. [8] and includes revenue from switchgrass hay at $65 Mg–1 less cost of synthetic fertilizers using prices in Table 2, cost of poultry litter ($27.55 Mg–1), if applicable, cost of litter and/or fertilizer application at $15 ha–1 for two annual applications, and a harvest cost of $25 Mg–1. Not included are establishment charges for switchgrass and a charge for land or management.

‡ Nutrient composition of poultry litter was assumed to be 4% N, 3% P2O5, and 3% K2O.

§ See Table 2 for historical prices of fertilizers and hay.

¶ Breakeven switchgrass price is calculated by solving for the switchgrass price that sets profit to zero.

The P and K response functions showed that using the high non-yield limiting nutrient rates (224 kg of P and 392 kg of K) for the N rate study was appropriate, as lesser or higher than the yield-maximizing P and K rates had little impact on yield. Nonetheless, the lack of explanatory power for the P and K response functions suggests that the exploration of the interaction of N, P, and K, may be fruitful to further explain P and K yield responses as already recommended by Kering et al. (2013a). This probably holds true more so for K than P since yield-maximizing rates for K were approximately twice or more of those for P and also because the K response function had greater slope than the response function for P (Fig. 1). All response functions show that the experimental rates for estimating yield response to specific nutrients was reasonable as estimated yield-maximizing rates were within the range of the experimental design. To summarize, using the N response function to calculate profit-maximizing N application rates was deemed appropriate as N use levels to maximize yield were highest and showed the greatest slope of any of the response curves (Fig. 1).

Table 3 also showed that the nutrient removal equations had high explanatory power. Their specification allowed estimation of profit-maximizing N application rate recommendations with attendant needs for P and K as based on their concentration in the harvested biomass.

As evident in Fig. 1, with $P_{N}$ set to $65$ Mg–1 and using average fertilizer prices, nutrient needs of the crop estimated to yield 15.7 Mg ha–1, across both harvests, were met using 186.3, 26.3, and 197.9 kg ha–1 of N, P, and K from synthetic sources, respectively. The yield-maximizing N rate, in comparison, was 371.3 kg ha–1 resulting in an estimated yield of 19.3 Mg ha–1. Yield-maximizing P and K rates were 164.6 and 335.7 kg ha–1, respectively. Hence, profit-maximization occurred at considerably lower than yield-maximizing input levels as a direct result of the slopes of the yield response functions as well as the value of switchgrass and fertilizer cost. With higher switchgrass prices and lower fertilizer cost, input use increases whereas the opposite holds true for a drop in switchgrass price and a rise in fertilizer price as shown in Table 4, where only fertilizer prices were modified. Table 5 shows the impact of changes in switchgrass price holding fertilizer price constant. Concomitantly, breakeven prices of switchgrass are also a function of input use and cost (Table 4).

Noteworthy in Tables 4 and 5 is that nutrient application of N, at the price levels for switchgrass and fertilizers examined, tends to be greater than removal of the same nutrient in biomass and more so at higher N application rates, be that from litter or synthetic sources. In those situations, N volatilization, N runoff, or increases in soil available N can be expected. For purposes of profitability calculations, however, we assume no N credit in those cases. Poultry litter application is limited to P removal to avoid environmental concerns. Should excess soil P levels exist, the P application recommendation should be ignored and would result in cost savings that would add to profitability and thereby also lower breakeven prices. At the same time, excess soil P conditions would preempt the use of poultry litter in those situations as well.

Profitability is higher with the use of poultry litter than without and thereby its use lowered the breakeven price. Breakeven prices are generally lower than hay prices (Table 2). However, hay prices in Table 2 include returns to land and management. Nonetheless, at the quality levels of hay observed (CP increased with N application as expected and estimated TDN was static), switchgrass hay compared favorably to other hay sources, even as CP and TDN are at the lower end of the quality spectrum of average Arkansas hay (Tables 4 and 5; Gadberry and Keaton, 2012). Nonetheless, feeding hay of this quality does meet the needs of dry beef cows. Lactating beef cows would require supplemental

<table>
<thead>
<tr>
<th>Poultry litter use</th>
<th>No</th>
<th>Yes§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switchgrass, $ Mg⁻¹</td>
<td>$55</td>
<td>$75</td>
</tr>
<tr>
<td>Est. yield, Mg ha⁻¹</td>
<td>13.0</td>
<td>17.0</td>
</tr>
<tr>
<td>Syn. N use, kg ha⁻¹</td>
<td>132</td>
<td>223</td>
</tr>
<tr>
<td>Syn. N use, kg ha⁻¹</td>
<td>22</td>
<td>29</td>
</tr>
<tr>
<td>Syn. K use, kg ha⁻¹</td>
<td>159</td>
<td>221</td>
</tr>
<tr>
<td>Litter applied, Mg ha⁻¹</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>N from litter, kg ha⁻¹</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>P from litter, kg ha⁻¹</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>K from litter, kg ha⁻¹</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>N removed, kg ha⁻¹</td>
<td>132</td>
<td>194</td>
</tr>
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<td>P removed, kg ha⁻¹</td>
<td>22</td>
<td>29</td>
</tr>
<tr>
<td>K removed, kg ha⁻¹</td>
<td>159</td>
<td>221</td>
</tr>
<tr>
<td>CP, % mass basis</td>
<td>6.69</td>
<td>7.42</td>
</tr>
<tr>
<td>TDN, % mass basis</td>
<td>51.54</td>
<td>51.27</td>
</tr>
<tr>
<td>Profit‡, $ ha⁻¹</td>
<td>14</td>
<td>288</td>
</tr>
</tbody>
</table>

† Profitability is calculated as specified in Eq. [8] and includes revenue from switchgrass hay at $65 Mg⁻¹ less cost of synthetic fertilizers using prices in Table 2, cost of poultry litter ($27.55 Mg⁻¹), if applicable, cost of litter, and/or fertilizer application at $15 ha⁻¹ for two annual applications and a harvest cost of $25 Mg⁻¹. Not included are establishment charges for switchgrass and a charge for land or management.

‡ See Table 2 for historical prices of fertilizers and hay.
§ Nutrient composition of poultry litter was assumed to be 4% N, 3% P₂O₅, and 3% K₂O.

feed and thereby raise feeding cost if switchgrass hay were used in comparison to hay of average quality in Arkansas.

**DISCUSSION**

The objective of this research was to determine fertilizer recommendations that vary with switchgrass and fertilizer prices when switchgrass is harvested for hay in early June and late July. This research showed that hay quality levels and fertilizer recommendations did vary with changes in fertilizer cost and the price of switchgrass. A supplemental spreadsheet was provided to assist hay and cattle producers with determining what hay quality and yield to expect if they follow fertilizer recommendations that vary with hay prices and fertilizer costs. As such, the tool provides information about the question of how hay of this quality would fit into their feed rations. For further comparison, the Energy Crop Analysis and Planning (ENCAP) decision support software provides a profit-maximizing fertilizer recommendation of 125 kg N ha⁻¹, 14 kg P ha⁻¹, and 103 kg K ha⁻¹ for Fayetteville, AR, on marginal soil using a switchgrass price of $65 Mg⁻¹ and average fertilizer prices without the use of litter (Lindsay et al., 2015). With that fertilizer recommendation, a single harvest of switchgrass destined to a biorefinery for conversion to energy, would yield an estimated 15.5 Mg ha⁻¹ in mid-November at lower cost given fewer harvest passes and less nutrient replacement cost than if harvested twice in the season for hay on similar soils. Managing switchgrass for hay at the same $65 Mg⁻¹ switchgrass and average fertilizer prices was estimated to yield 15.7 Mg ha⁻¹ using 186 kg N ha⁻¹, 29 kg P ha⁻¹, and 198 kg K ha⁻¹. Nutrient removal is higher compared with late season harvest because harvest occurs during the growing season as opposed to after senescence when N, P, and K translocate back to perennializing crown and roots or are recycled from plant material dropping to the soil.

Overall, integrating switchgrass into forage systems may allow producers increased flexibility to respond to variations in potential biomass, forage, and livestock markets because switchgrass is well adapted to growth on marginal soils. Switchgrass hay at estimated yields and hay quality may serve to lower hay cost for cow–calf operations that can use low CP and TDN hay as it can be grown using (i) less fertilizer per unit of hay produced, or (ii) less land resources in comparison with bermudagrass or tall fescue, which are common forage species in the mid-southern United States.

**SUPPLEMENTAL MATERIAL**

The supplemental file is an Excel™ spreadsheet that allows the user to modify the price for switchgrass and costs of fertilizers and field operations. The spreadsheet plots yield response functions to nutrient applications and further assists with fertilizer application rate recommendations that vary by nutrient source, nutrient cost, and switchgrass price. It estimates hay quality for each cutting, highlighting crude protein and total digestible nutrient concentrations. It also calculates a breakeven switchgrass price. The spreadsheet was designed for a Windows operating system and uses macros.

**REFERENCES**


