# Yield and Nutrient Concentration Response to Switchgrass Biomass Harvest Date

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**ABSTRACT**

**Timing of biomass removal from stands of switchgrass (*Panicum virgatum* L.) impacts the nutrient content of harvested material and fertilizer requirements for subsequent growing seasons. This study was conducted to determine the change in N, P, and K content of harvested switchgrass biomass as a function of the harvest date and to determine the economic consequences of an extended harvest window. Data were produced in a randomized complete block study conducted at the Oklahoma Agricultural Experiment Station, Stillwater, with six replications over three harvest seasons from November of 2007 to March of 2010. Treatments on the established stand of cultivar Kanlow consisted of five harvest dates separated by about 30 d beginning in late November. Regression equations were used to fit yield and N, P, and K concentration response to the harvest date. Delaying harvest beyond December resulted in an average 5.4% decline in harvested biomass per month. Delaying harvest beyond November did not result in a significant change in the N concentration in the harvested biomass. However, delaying harvest did result in a significant decrease in both P and K content in the harvested biomass. Point estimates from the response functions were used to estimate production cost for each of five harvest dates beginning with 30 November and ending with 30 March. The quantities of $P_2O_5$ and $K_2O$ fertilizer that would be required to replace the P and K removed with the biomass were used in the budgets. Biomass production cost was similar across harvest dates.**

Switchgrass has been described as a model native U.S. species to produce biomass that could be used as biorefinery feedstock (Sanderson et al., 2006; McLaughlin et al., 2002). The U.S. Department of Energy's (2011) Billion-Ton Update reported that 16 to 24 million ha of U.S. cropland and pasture could be converted to produce dedicated energy crops such as switchgrass. One advantage of switchgrass is that it can grow in a variety of environmental conditions including on low quality land and under relatively dry conditions (Lewandowski et al., 2003). Prior studies have reported yield decreases associated with delaying switchgrass biomass harvest into the winter (Parrish et al., 1997; Casler and Boe, 2003; Sanderson et al., 2006).

Most studies budgeted switchgrass production costs as if it were a traditional crop (Epplin, 1996; Brown et al., 2000; Perrin et al., 2008; Mooney et al., 2009). Switchgrass is assumed to be harvested during a narrow time frame after maturity when maximum dry matter yield can be achieved (Vogel et al., 2002). This system would result in maximum harvested yield per hectare but would not necessarily be the most economically efficient system to deliver a flow of biomass to a biorefinery. In the southern plains of the United States, the switchgrass harvest window could extend over many months. An extended harvest season would require fewer harvest machines per biorefinery thereby reducing overall harvest machinery fixed costs (Epplin and Haque, 2011; Haque and Epplin, 2012). An extended harvest window would enable a just-in-time delivery system during harvest months and reduce overall storage cost (Cundiff and Marsh, 1996; Larson et al., 2010; Grisso et al., 2013). However, with an extended harvest window, the expected harvestable yield and the expected fertilization requirement for the succeeding year might differ depending on the harvest date. If harvest is delayed until after the first frost and the initiation of senescence, biomass yield will be maximized and nutrients will have translocated, which may reduce the quantity of fertilizer needed for biomass production in subsequent years (Chapin, 1980; McLaughlin and Kszos, 2005). However, if harvest is delayed, plants may lodge, and delaying harvest until late winter may result in lower harvestable biomass yields. Previous studies have hypothesized that the machinery cost savings and savings from reduction in storage costs from an extended harvest may be sufficient to offset the expected yield losses (Haque and Epplin, 2012).

Nutrient removal by the plant is expected to differ with time of harvest (Fixen, 2007). Information on the economic consequence of the tradeoff between harvestable yield, nutrient removal, storage cost, and harvest machinery investment is sparse (Grisso et al., 2013). Knowledge of the tradeoffs between nutrients removed and biomass yield as switchgrass harvest is delayed is essential to determine the most economically efficient production system. The

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purpose of the present study is to estimate switchgrass biomass N, P, and K content as well as biomass yield as functions of harvest date and to determine the cost per unit of biomass also as a function of the harvest date.

Data were produced in a field experiment over three production seasons from 2007 to 2010. The aim of the experiment was to determine biomass nutrient (N, P, K) concentration and biomass yield by harvest date. Statistical methods were used to determine the biomass nutrient content and the dry biomass yield as a function of harvest date. Point estimates from these response functions were used to prepare enterprise budgets for each of five harvest dates to determine the economic consequences of an extended harvest season on feedstock production cost.

## MATERIAL AND METHODS

### Agronomic

The field experiment was conducted at the Oklahoma Agricultural Experiment Station in Stillwater (36°7.98′ N, 97°6.26′ W). The randomized complete block experiment with five treatments and six replicates was conducted over 3 yr from 2007 to 2010. The Kanlow switchgrass stands were established in 1998. Before beginning the experiment no fertilization or other chemical treatments had been applied on the switchgrass stands for 3 yr to ensure no effects of previous fertilization on yield. Also during the experiment no fertilization occurred. The only treatment on the established switchgrass stand were the harvest dates (24–29 November; 21 or 22 December; 20–29 January; 23–27 February; and 26 March–3 April) with one harvest per year per plot. Post seed set dormancy is a gradual process and for the region of the study begins in November. December and later harvest dates are post-senescence. Monthly precipitation levels for the site and the years of the study are reported in Table 1. Monthly average daily temperatures are reported in Table 2.

For each treatment biomass yield was recorded with the moisture content at harvest after swathing and baling using a swather (John Deere MoCo–Model 630, 22 John Deere Co., Moline, IL) and a baler (John Deere–Model 568, John Deere Co., Moline, IL). On each harvest date additional random and hand grabbed samples of nearly 500 g were collected. The sample biomass was dried at 55°C in a forced air oven for 3 to 7 d. After drying, the dry matter was measured. Dry biomass was ground and passed through a 1 mm sieve and analyzed for the biochemical content of N, P, and K (Makaju et al., 2013).

Table 1. Monthly precipitation at site for years of the study and the 10- yr average (cm).†

| Month | 2007 | 2008 | 2009 | 2001–2010 10-yr avg. |
|---|---|---|---|---|
| | cm | | | |
| January | 3.40 | 1.42 | 0.43 | 3.40 |
| February | 1.07 | 6.55 | 5.28 | 3.81 |
| March | 13.87 | 10.54 | 9.22 | 7.02 |
| April | 10.54 | 14.58 | 12.88 | 8.16 |
| May | 26.49 | 16.18 | 8.28 | 12.68 |
| June | 42.52 | 12.50 | 4.39 | 15.51 |
| July | 17.81 | 12.70 | 12.60 | 9.76 |
| August | 3.33 | 3.35 | 19.05 | 8.82 |
| September | 11.68 | 4.19 | 7.80 | 7.05 |
| October | 8.38 | 5.26 | 18.39 | 7.54 |
| November | 2.21 | 6.73 | 3.94 | 3.50 |
| December | 2.67 | 1.98 | 1.40 | 3.08 |

† Source: www.mesonet.org/index.php/weather/monthly_rainfall_table/stil (accessed 5 Nov. 2013).

For regression models, a continuous time variable was constructed for the harvest date with 1 July set equal to one and 30 June set equal to 365. A visual inspection of scatter plots of both yield and nutrient content was conducted to formulate hypotheses on functional forms and expected parameter signs in the regression equations. A scatter plot of the observed yields against the harvest dates indicated no perceptible difference between November and December yields. However, yields declined from December to the last harvest dates in early April. Because the observation of the scatter plot of yield revealed that yield decline began after the December harvest, the November harvest biomass yield data were dropped. Two functional forms (linear and inverse transformation) were estimated using the yield data from December to April. The equations were estimated using SAS PROC MIXED (SAS Institute, 2008) with year and replication modeled as random effects. Since the two models have the same number of parameters, the likelihood ratio test proposed by Pollak and Wales (1991) was used to compare the two non-nested functional forms. Misspecification tests for non-normality and heteroskedasticity were conducted to detect the presence of any departure from normality or heteroskedasticity. The D’Agostino (D’Agostino et al., 1990) K2 test for normality based on skewness and kurtosis was used to test non-normality and the RESET test for heteroskedasticity was conducted to test the null hypothesis of homoskedastic residuals.

Scatter plots of the P and the K biomass elemental concentration against the harvest dates indicate decreasing percentages for the two elements as the harvest date is delayed. However, scatter plots of N concentration in the harvested biomass did not reveal a perceptible change across harvest months. Two functional forms (linear and the inverse transformation) were also specified to estimate N, P, and K content as a percentage of dry matter for the five harvest treatment dates using the continuous time variable. The encompassing non-nested hypothesis test (Greene, 2012) was used to select the model that best fits the data. Misspecification tests were conducted to test normality of residuals and heteroskedasticity. Normality was tested using the K2 test. The RESET test was used to test heteroskedasticity.

Table 2. Monthly average daily temperatures at site for years of the study and the 10-yr average (°C).†

| Month | 2007 | 2008 | 2009 | 2001–2010 10-yr avg. |
|---|---|---|---|---|
| | °C | | | |
| January | 1.2 | 3.1 | 1.6 | 2.8 |
| February | 4.1 | 3.7 | 8.3 | 4.5 |
| March | 14.6 | 10.2 | 11.6 | 10.6 |
| April | 13.3 | 14.3 | 15.2 | 16.1 |
| May | 20.7 | 20.6 | 19.2 | 20.5 |
| June | 23.6 | 25.5 | 27.2 | 25.2 |
| July | 26.1 | 28.0 | 27.2 | 27.7 |
| August | 28.3 | 26.4 | 25.4 | 27.2 |
| September | 23.0 | 21.1 | 20.7 | 22.0 |
| October | 17.3 | 15.2 | 12.4 | 15.5 |
| November | 10.1 | 9.2 | 11.5 | 10.2 |
| December | 2.5 | 3.1 | 0.9 | 3.8 |

† Source: http://cig.mesonet.org/~gmcmanus/monthly_meso/meso_month.cgi?beginmonth=01&beginyear=1994&endmonth=07&endyear=2013&stid=STIL&parms=9AVG& SUBMIT=Submit (accessed 5 Nov. 2013).

Because the plots in the experiment were not fertilized and had not been fertilized for 3 yr before the initiation of the experiment, biomass yield from the harvest date plots was expected to be substantially lower than yield from plots that are fertilized and grown for commercial purposes. Fertilized plots of Kanlow switchgrass grown elsewhere at the experiment station during the same years were harvested to produce a yield estimate more reflective of fields commercially managed to produce biomass. The fertilized plots were established in June 2006 with four replications. Soil P and K levels in the fertilized plots had been brought up to sufficient levels before planting. Recommended N rates for switchgrass differ due to regional differences in the length of the growing season, precipitation, and expected yield (Thomason et al., 2004; Fike et al., 2006; Schmer et al., 2008; Haque et al., 2009; Boyer et al., 2012). Haque et al. (2009) estimated an optimal level of 65 kg N ha$^{-1}$ yr$^{-1}$. Schmer et al. (2008) reported a mean application rate of 74 kg N ha$^{-1}$ yr$^{-1}$ in their study of switchgrass production in the western U.S. Great Plains. Fike et al. (2006) used 100 kg N ha$^{-1}$ yr$^{-1}$. Boyer et al. (2012) found that the optimal N rate ranged from 63 to 200 kg ha$^{-1}$ yr$^{-1}$ depending on soil type, N price, and biomass price. Based on the findings of prior studies, the plots were fertilized with 90 kg N ha$^{-1}$ each April and were harvested once per year after frost in November. The harvest and measurement methods were the same as those used on the unfertilized experimental plots.

Yield estimates for economic analysis were synthesized by using the yields obtained from the fertilized plots as harvested in November after frost as the base November–December yield. For yield estimates for subsequent harvest dates, the base yields were adjusted by the percentage changes in harvested biomass as estimated with the yield response to the harvest date function. Estimates of nutrient content from the response functions for specific dates were multiplied by the synthesized biomass yields to obtain an estimate of nutrient removal for plants assumed to be fertilized and managed to produce commercial biomass. The validity of these estimates depends on the assumption that the percentage change in yield response to the harvest date, and the percentage change in nutrient content by the harvest date, is the same for fields that would be fertilized as it was for the unfertilized plots used to estimate yield and nutrient response to harvest date.

### Economics

The decision maker's objective is assumed to be to select the harvest date that maximizes the returns to the resources used for switchgrass production. An objective function may be specified as follows:

$$\max_{HD} E(\pi) = \max(p - HCB)Y(HD_t) - r_N N - r_P P(HD_{t-1}) - r_K K(HD_{t-1}) - OC \qquad [1]$$

where $E(\pi)$ is the expected annual profit (\$ ha$^{-1}$ yr$^{-1}$), $p$ is the price of biomass feedstock in \$ Mg$^{-1}$, $HCB$ is the cost of operations that depend on quantity of biomass harvested (baling, wrapping, and transportation [\$ Mg$^{-1}$]), $Y$ is the dry biomass yield (Mg ha$^{-1}$) that depends on the harvest date $HD_t$ for the current year, $HD_{t-1}$ is the harvest date for the previous year, $OC$ is the cost of other inputs that do not vary across harvest date (establishment, reseeding, land lease, mowing, raking, other inputs, and the associated interest on operating capital [\$ ha$^{-1}$ yr$^{-1}$]), $r_N$, $r_P$, and $r_K$ represent the prices of N, P, and K, respectively (\$ kg$^{-1}$); $N$, $P$, and $K$ are the quantities (kg ha$^{-1}$) of N, P, and K, respectively. Since the price of biomass is unknown, for a given level of fertilizer prices, other costs, and a selected harvest date, the expected profit may be set equal to zero and the equation may be used to determine the breakeven price (\$ Mg$^{-1}$) which is equivalent to the cost of producing a megagram of biomass feedstock.

Since the fertilized plots received an annual application of 90 kg N ha$^{-1}$yr$^{-1}$ and since this level of N fertilization is within the range reported in prior studies, N fertilizer was budgeted at a rate of 90 kg ha$^{-1}$ of N across all harvest dates. The level of P applied as $P_2O_5$ and K applied as $K_2O$ can be determined by multiplying the nutrient concentration for the date as predicted by the regression equations, by the yield for the harvest date as simulated using the fertilized experiment yield. For the purposes of budgeting, by this measure, it is assumed that the level of P and K removed in the biomass would be replaced by fertilizer.

Estimates of yields and fertilizer requirements were obtained for each of five harvest dates (30 November, 30 December, 30 January, 28 February, and 30 March). A standard enterprise budget was prepared for each of these five harvest dates. Budgeted field operations are based on the assumptions of Turhollow and Epplin (2012). Based on switchgrass yield and estimated biomass nutrient content, the cost to produce and deliver switchgrass feedstock to a biorefinery was calculated depending on harvest date. The cost scenarios assume an amortized establishment cost of \$41.70 ha$^{-1}$ for a 10-yr amortization period. The land lease cost was estimated at \$111.15 ha$^{-1}$. The baseline fertilizer prices were budgeted at \$1.23 per kg of N, \$2.70 per kg of P and \$1.37 per kg of K. Sensitivity analysis was conducted by reducing and increasing the fertilizer prices by 50% to reflect the consequences of alternative fertilizer prices.

The fertilizer application cost was estimated at \$5.97 ha$^{-1}$ assuming that the three fertilizers would be applied in blended granular form in one application. The transportation operations were assumed for a 1-h trucking distance that is equivalent to a cost of \$3.75 Mg$^{-1}$. Some cost elements such as the establishment, reseeding, maintenance, land lease, mowing, and raking and the associated interest on operating capital, are evaluated on a per hectare basis. Other cost elements such as baling, wrapping, and transportation costs are proportional to harvested biomass quantity.

Since predicted values from regression equations were used to estimate feedstock production, the cost estimates would be heretoskedastic. Thus, a standard *F* test would not be appropriate to test for differences in cost across harvest dates. Therefore, to test for differences across the mean estimates of costs for the five budgeted harvest dates, the White (White, 1980) heteroskedasticity consistent covariance matrix option in SAS PROC REG was used (SAS Institute, 2008).

## RESULTS

### Agronomic

Two functional forms (linear and inverse transformation) with the continuous time variable were used to estimate biomass yield response to harvest date. Data from December to April were used to conduct the estimation. The likelihood ratio test indicated that the inverse transformation functional form provides a better fit for

Table 3. Switchgrass yield response to harvest date estimated with both a linear and an inverse transformation functional form with data from plots harvested from 21 December to 3 April.

| Variable | Linear model† | Inverse transformation |
|---|---|---|
| Intercept | 8.6281* | 3.4637 |
| | (1.80)‡ | (1.78) |
| Date§ | –0.01190* | |
| | (0.0050) | |
| Invdate¶ | | 544.42* |
| | | (0.0257) |
| –2 loglikelihood | 298.3 | 277.1 |

* Statistically significant at the 0.05 probability level.

† The dependent variable is the dry biomass yield (Mg ha$^{-1}$).

‡ Numbers in parentheses are standard errors.

§ Date is the number of days from July first to the date of harvest (e.g. 1 July = 1; 1 January = 185). Based on the data used to fit the function the relevant range is from 21 December (Day 174) to 3 April (Day 277).

¶ Invdate is the inverse transformation of the harvest date. For example, the value for a harvest date of 24 November is 185$^{-1}$, which is equal to 0.005405.

the yield data obtained from harvests ranging from 21 December to 3 April (Table 3). The normality K2 test did not detect the presence of non-normality with the inverse transformation model (K2 = 1.59 and ProbK2 = 0.44). The RESET test for heteroskedasticity also found that the null hypothesis of homoskedasticity could not be rejected at the 5% significance level ($P = 0.42$).

Based on the inverse transformation model the predicted yield declined by 6.7% from 30 December to 30 January; by 5.1% from 30 January to 28 February; and by 4.3% from 28 February to 30 March. By this measure, from 30 December to 30 March, the average decline in harvested dry matter was 5.4% per month. The results are consistent with previous work on the impact of delaying harvest over the winter period (Thomason et al., 2004). However, most previous work has reported a continuously declining tendency in harvestable yield from the switchgrass maturity in late October to the late winter period (Fike et al., 2006; Guretzky et al., 2010). In the present study, the decline in harvestable yield started after December.

The percentages of N, P, and K in the harvested biomass response to harvest date were also estimated using a linear and an inverse transformation functional form. Results are reported in Table 4. The slope coefficients for both functional forms for the percentage of N response to harvest date are not significantly different from zero. This finding indicates that the percentage of N in the harvested biomass did not change as harvest was delayed from November to March. This finding is consistent with that reported by Guretzky et al. (2010) who also hypothesized that N translocation from the aboveground biomass to the root system would occur between the early reproductive stage and the seed set.

For P and K contents the inverse transformation of the harvest date was the only variable that was statistically significant in the non-nested encompassing model ($P = 0.04$ and 0.0003 for the P and K biomass content estimation, respectively). Therefore, for the economic analysis the inverse transformation functional forms were used to estimate P and K concentrations in the biomass as functions of the harvest date. The normality test for the biomass P content estimation indicates that the null hypothesis of normality of the residuals is rejected at the 5% significance level (K2 = 21.113 and PK2 = 0.00002). The empirical option of the SAS MIXED (SAS Institute, 2008) procedure was used to adjust for non-normality of the residuals. The heteroskedasticity tests indicates that the null hypothesis of homoskedasticity cannot be rejected at 5% significance level for both the P and K content estimation.

Table 4 summarizes the results for P and K concentration response to the harvest date. The inverse transformation of the harvest date was highly significant in both equations suggesting declining nutrient content as harvest is delayed. Predicted values for the biomass P and K content are plotted in Fig. 1, which illustrates the decline in nutrient concentration corresponding to delayed harvest. The results support the hypothesis that biomass nutrient content would decline when harvest is delayed into late winter. The results are consistent with studies by Guretzky et al. (2010) and Kering et al. (2012), which suggest decreasing nutrient content when harvest is delayed. The predicted K content of switchgrass biomass harvested in late November is 259% greater than the K content of switchgrass harvested in late March. The predicted P content of switchgrass biomass harvested in late November is 84% greater than the P content of switchgrass harvested in late March. Whereas the predicted biomass yield of switchgrass harvested in late December is only 18% greater than the predicted biomass yield of switchgrass harvested in late March.

Table 4. Nitrogen, P, and K in harvested biomass (%) response to harvest date.

| | Biomass N content† | | Biomass P content† | | Biomass K content† | |
|---|---|---|---|---|---|---|
| Variable | Linear model | Inverse transformation | Linear model | Inverse transformation | Linear model | Inverse transformation |
| Intercept | 0.4453 | 0.3837 | 0.1305* | –0.0034 | 0.4524* | –0.1529* |
| | (0.1855)‡ | (0.1792) | (0.0074) | (0.0089) | (–0.023) | (0.02) |
| Date§, | –0.00027 | | –0.00032*** | | –0.00146*** | |
| | (0.000839) | | (0.00003) | | (–0.0001) | |
| Invdate¶ | | 0.9890 | | 13.16*** | | 59.83*** |
| | | (33.4118) | | (1.98) | | (3.92) |
| Encompassing test *P* value | | | 0.83 | 0.04 | 0.22 | 0.0003 |

* Statistically significant at the 0.05 probability level.

*** Statistically significant at the 0.001 probability level.

† The biomass N, P, and K content are elemental N, P, and K content measured as percent of dry biomass.

‡ Numbers in parentheses are standard errors.

§ Date is the number of days from 1 July to the date of harvest (e.g. 1 July = 1; 1 January = 185). Based on the data used to fit the function the relevant range is from 24 November (Day 147) to 3 April (Day 277).

¶ Invdate is the inverse transformation of the harvest date. For example, the value for a harvest date of 24 November is 185$^{-1}$.

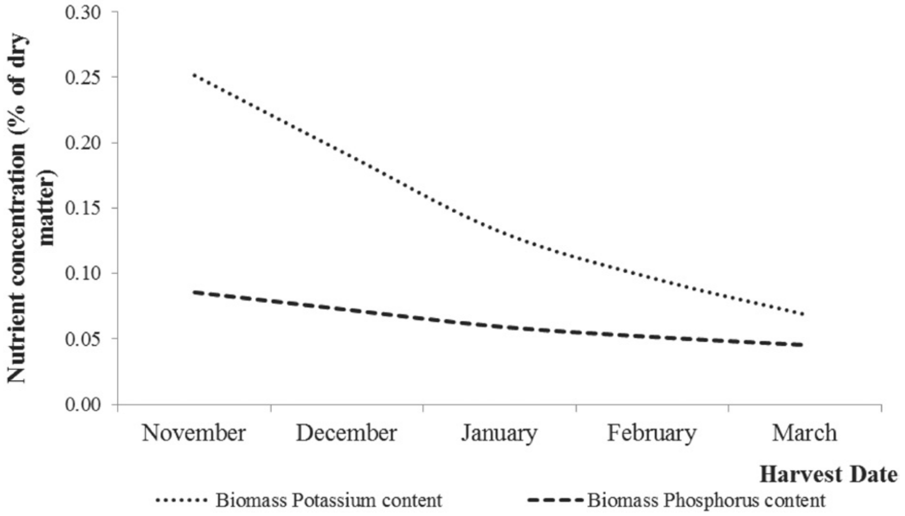

Fig. 1. Predicted switchgrass elemental P and K concentration in harvested biomass by harvest date.

For the economic analysis, the assumption is made that the P and K that is removed will be replaced with fertilizer.

### Economic

The average yield of the November harvested fertilized plots was 14.40 Mg ha$^{-1}$. This quantity is assumed to be the base yield for economic analysis. Since the statistical analysis did not show a significant yield difference between November and December harvested plots, the base yield of 14.40 Mg ha$^{-1}$ is also assumed for December harvests. Yield declines as estimated by the regression model of 6.7, 5.1, and 4.3% were applied to the base yield to obtain biomass expected yield estimates of 13.43 Mg ha$^{-1}$ for a 30 January harvest; 12.76 Mg ha$^{-1}$ for a 28 February harvest; and 12.21 Mg ha$^{-1}$ for a 30 March harvest (Table 5).

The predicted values for P and K concentration by harvest date from the regression equations were used to determine the quantity of $P_2O_5$ and $K_2O$ fertilizers that would be required to replace the P and K removed with the biomass. The estimated $P_2O_5$ and $K_2O$ quantities that would be required to replace the P and K removed with harvested biomass are plotted in Fig. 2. The budgeted quantities of $P_2O_5$ and $K_2O$ per hectare, for each of the five budgeted harvest dates, are presented in Table 5.

The cost to deliver 1 Mg of switchgrass is estimated for each of five harvest dates. The results are summarized in Table 6. For the baseline fertilizer prices of \$1.23 kg$^{-1}$, \$2.70 kg$^{-1}$, and 1.37 kg$^{-1}$ for N, P, and K, respectively, the mean production cost is estimated at \$59 Mg$^{-1}$ for the biomass harvested in November (Table 6). For biomass harvested in December the production cost is estimated at \$58 Mg$^{-1}$, which is the lowest production cost (Table 6). When harvest is delayed until the late winter months, the production cost increases from \$59 Mg$^{-1}$ in January to \$60 Mg$^{-1}$ for February and March harvest (Table 6).

When the baseline prices of fertilizers are reduced by 50%, the production cost is estimated to be \$52 and \$54 Mg$^{-1}$ for the 30 November and the 30 March harvest dates, respectively (Table 6). With the low fertilizer price scenario, the production cost is estimated at \$53 Mg$^{-1}$ for the 30 January harvest and at \$54 Mg$^{-1}$ for switchgrass harvested on 28 February and 30 March. Reducing the fertilizer cost by 50% reduced the production cost by 10 to 12%.

In a second sensitivity analysis scenario the fertilizer base prices are increased by 50% to reflect the impact of a fertilizer price increase on the production cost. With the higher prices, the production cost are estimated to be between \$64 and \$66 Mg$^{-1}$. The 50% increase in prices resulted in an increase in the production cost between 8 and 12% (Table 6). Table 6 also includes the fertilization cost percentage of the total production cost. For the baseline fertilizer prices, fertilizer costs decline from 23 to 19% of the total production cost as harvest is delayed from November to March.

Estimated production costs are very similar across harvest dates ranging from 30 November to 30 March (Table 6). Based on the White (1980) robust F-test the difference in production cost across the 5 mo and the six replications was not statistically significant ($P \geq 0.50$). The findings are that even though there were significant declines in harvestable yield across harvest months there was not a significant increase in production cost because less P and K was removed from plots on which the harvest was delayed.

## DISCUSSION

Economically competitive biorefineries could be expected to operate continuously throughout the year and require a steady flow of feedstock. A perennial grass such as switchgrass has as a potential advantage in that in some climate regions, the harvest window may extend over many months. Switchgrass feedstock production with an extended harvest window and a one cut

Table 5. Biomass removed and budgeted quantities of $P_2O_5$ and $K_2O$ estimated to be required to replace nutrients removed in harvested biomass by harvest date.

| Harvest date | Biomass removed† | $P_2O_5$‡ | $K_2O$‡ |
|---|---|---|---|
| | Mg ha$^{-1}$ | kg ha$^{-1}$ | |
| 30 November | 14.40 | 27 | 41 |
| 30 December | 14.40 | 23 | 30 |
| 30 January | 13.44 | 18 | 21 |
| 28 February | 12.76 | 15 | 14 |
| 30 March | 12.21 | 13 | 10 |

† The removed biomass quantities are calculated by adjusting the observed biomass yield from the fertilized plots with the yield decline rate observed in the unfertilized plots.

‡ $P_2O_5$ and $K_2O$ equivalent were calculated using the predicted values from regression of P and K biomass concentration response to harvest date from Table 4.

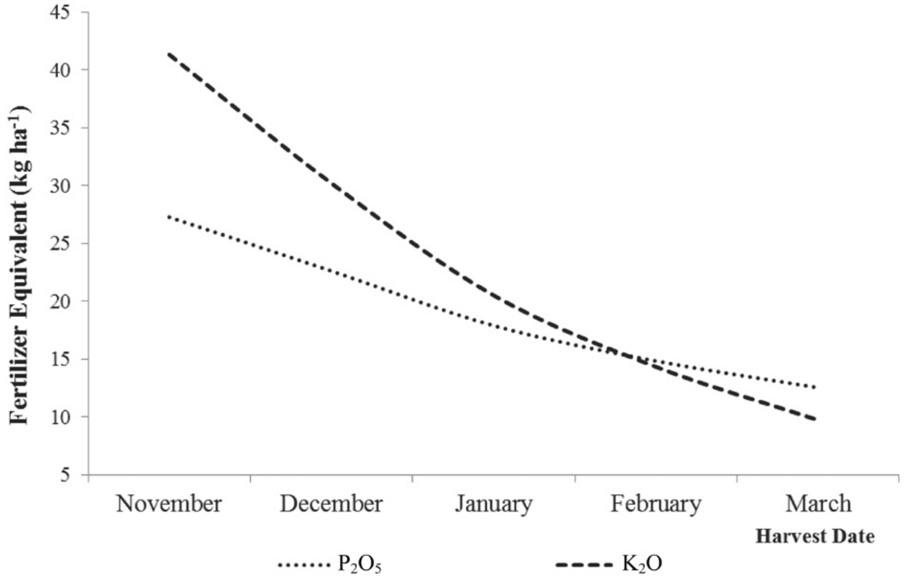

Fig. 2. Switchgrass fertilizer quantity equivalent in the biomass removed by harvest date.

system has been examined by several studies. However, these prior studies did not have field estimates of the yield and fertilization consequences of an extended harvest window (Tembo et al., 2003; Mapemba et al., 2007; Hwang et al., 2009). Lengthening the harvest window has the potential to reduce the number of harvest machines required to support a biorefinery thereby reducing harvest costs (Epplin and Haque, 2011; Haque and Epplin, 2012). An extended harvest window would also reduce biomass storage cost (Cundiff and Marsh, 1996; Sanderson et al., 1997; Larson et al., 2010; Grisso et al., 2013).

The present study considered switchgrass biomass feedstock production with a 5 mo harvest window from November to March. The objective was to investigate the combined economic consequences of changes in harvestable yield and in nutrient removal, as harvest is delayed. Results suggest that as harvest is delayed into the winter months in the region of the study, biomass harvestable yield decreases. However, delaying harvest resulted in reduced P and K fertilizer requirements in subsequent years. In general, the reduction in fertilizer cost largely offsets the value of the reduced yield such that the cost to deliver a megagram of biomass is not statistically significantly different across harvest months. By this measure, harvesting switchgrass biomass over an extended window could be expected to be an economically viable business strategy.

A business strategy to extend the harvest season into March would result in a lower average harvestable yield per hectare. Hence, more hectares would be required to support a biorefinery with fixed feedstock requirements. Some of these additional hectares could be expected to be located at greater distances from the biorefinery. Average transportation distances and transportation cost would be greater. However, field storage losses of harvested biomass would be expected to be lower relative to a narrow harvest window (Sanderson et al., 1997). A more comprehensive modeling approach would be required to fully assess the economic consequences of the changes in yield, fertilizer requirements, storage requirements, and transportation costs as an extended harvest window is considered. Additional research would be necessary to evaluate the tradeoffs that affect biorefinery production cost.

As discussed, the percentage changes in yield and nutrient content were estimated from plots that were not fertilized during the study and had not been fertilized for 3 yr before the study. This was done to ensure no effect of previous fertilization on yield. A limitation of the economic analysis component of the study is that the percentage change in yield and the percentage change in nutrient concentration in response to the harvest date were assumed to be the same on a fertilized plot as on the unfertilized plots. Additional research would be required to confirm this hypothesis.

Table 6. Cost to deliver 1 Mg of switchgrass by harvest date and percentage of fertilizer cost in the total cost.

| | 50% decrease in baseline fertilizers prices† | | Baseline fertilizers prices‡ | | 50% increase in baseline fertilizers prices | |
|---|---|---|---|---|---|---|
| Harvest date | Production cost | Fertilizer cost percentage of production cost | Production cost | Fertilizer cost percentage of production cost | Production cost | Fertilizer cost percentage of production cost |
| | $\$\ \mathrm{Mg}^{-1}$ | % | $\$\ \mathrm{Mg}^{-1}$ | % | $\$\ \mathrm{Mg}^{-1}$ | % |
| 30 November | 52 | 13 | 59 | 23 | 66 | 31 |
| 30 December | 52 | 12 | 58 | 21 | 64 | 29 |
| 30 January | 53 | 12 | 59 | 20 | 65 | 27 |
| 28 February | 54 | 11 | 60 | 20 | 65 | 27 |
| 30 March | 54 | 11 | 60 | 19 | 66 | 26 |

† The estimated cost is calculated by considering nutrient removed in the switchgrass biomass. When evaluated for all the replications and compared across months the production costs were not statistically different at 5% significance level.

‡ The baseline fertilizer prices are $\$1.23\ \mathrm{kg}^{-1}$, $\$2.70\ \mathrm{kg}^{-1}$ and $1.37\ \mathrm{kg}^{-1}$ for N, P, and K, respectively.

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