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# Does Soil Nutrient Mining and Remobilization Affect Harvest Strategy and Nutrient Management Decisions for Switchgrass Feedstock?

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**Does Soil Nutrient Mining and Remobilization Affect Harvest Strategy and Nutrient Management Decisions for Switchgrass Feedstock?**

## ABSTRACT

Conventional analytical methods used to determine the most economical farmer-based harvest system and corresponding nutrient management strategy for producing switchgrass (*Panicum virgatum L.*) feedstock do not consider agronomic and subsequent economic problems associated with soil nutrient mining. The objective of this study was to determine the long-term, economically sustainable harvest system and corresponding rates of N, P and K for producing switchgrass feedstock in the southern Great Plains. Data collected from a four-year, two-location agronomic field trial in south-central Oklahoma were used for analyses that included two harvest systems, including (1) a single cut after a hard freeze, after plant senescence (WNTR), and a summer cut at plant maturity in July followed by a second cut after a hard freeze, after plant senescence (SMWNTR). Each system received 0, 45, 90, 135, 179, and 224 kg of N $ha^{-1}$ $yr^{-1}$, and received 67 and 135 kg $ha^{-1}$ $yr^{-1}$ of $P_2O_5$, and $K_2O$, respectively. A standard forage analysis was used to determine the concentrations of N, P and K nutrients in the feedstock harvested from each plot in each year and location and converted to N, $P_2O_5$ and $K_2O$ (kg $ha^{-1}$) equivalents. These data were used to determine the extent of soil nutrient mining or nutrient remobilization for each harvest system. Two separate econometric models were estimated and used with enterprise budgeting techniques to compare the effects of harvest system and nutrient levels on yield and economic net return. Model 1 represents the conventional economic approach that uses the fertilizer treatments applied in the experiment. Model 2 reflects the long-term, economic sustainability approach and uses the nutrient concentration levels calculated from the switchgrass forage samples collected in the study. For a farm-gate feedstock price of \$83 $Mg^{-1}$ and nutrients priced at 2012 market rates, the results showed that it was economically sustainable to harvest only once after a hard freeze (i.e., the WNTR system) and apply 84, 28 and 50 kg $ha^{-1}$ $yr^{-1}$ of N, $P_2O_5$ and $K_2O$, respectively. For this base-case scenario, farmers earned \$79 $ha^{-1}$ more net return with the economic sustainability approach compared to the results generated from the conventional economic approach. However, the comparative results between the two economic approaches are quite sensitive to the assumptions about yield response to nutrient concentration levels and assumptions about the percentage of nutrients remobilized in the WNTR system that are actually available for reuse by switchgrass plants.

*Key words:* Switchgrass, economic sustainability, cellulosic biomass, nitrogen, harvest system

## 1. Introduction

Switchgrass (*Panicum vigatum* L.) has been identified by crop scientists and public policy makers as a leading source of cellulosic feedstock for conversion into bioenergy products in the southern Great Plains—a region in the US that has a comparative advantage in growing native perennial grasses for conservation programs, wildlife habitat, and livestock enterprises.

Published reports (Aden et al. 2002; Eggeman and Elander 2005; Kazi et al. 2010; Wu, Sperow, and Wang 2010; Humbird et al. 2011; Haque and Epplin, 2010) indicate that a large-scale biorefinery (≥ 50 million gallons per year production capacity) will require between $100 and $500 million in initial investment capital, depending on the conversion technology utilized (e.g., enzymatic hydrolysis, thermochemical pyrolysis, gasification, etc.). Previous studies estimated delivered switchgrass feedstock cost for a 1,814 Mg $d^{-1}$ for a biorefinery using a gasification technology with an expected 15-20-year life of the biorefinery (Epplin 2007; Haque and Epplin 2010). To put this into some perspective, such a biorefinery would require 162 ha of harvested switchgrass feedstock daily, assuming each centrally located farm can produce 11.2 Mg $ha^{-1}$ $yr^{-1}$. Prior to investing $500 million in a large-scale biorefinery, investors want to ensure that they have access to local and continuous long-term supply of feedstock for a number of years (15 to 20 years) in order to minimize the risk of the investment. It is important for producers that are providing feedstock to such a biorefinery to have reliable information about the actual fertilizer requirements of the plants in order for them to maintain productive levels of nutrient in the soil in order to produce long-term, economically sustainable supplies of switchgrass feedstock.

Data collected from multi-location, multi-year agronomic field trials in the south-central Oklahoma show that significant amount of nutrients (i.e., N, P and K) in excess of levels supplied via controlled treatments were removed (mined) from the soil by switchgrass plants that were harvested at the time of plant maturity, prior to plant senescence, in July (Guretzky et al. 2011). Conversely, data from the same studies showed that significant levels of N, P and K nutrients supplied to switchgrass were remobilized back to the root zone (and to some extent, back to the soil) in plants that were harvested in the winter after a hard freeze, after plant senescence. Reynolds et al. (2000) also reported that, on average over 5 years, total N concentration of harvested switchgrass feedstock was about 112 kg $ha^{-1}$ for a two-cut harvest system (summer and winter) with high N concentration of 91 kg $ha^{-1}$ of feedstock from the summertime harvest. Whereas, N concentration was only 49 kg $ha^{-1}$ on feedstock harvested only once after a hard freeze in the winter, after plant senescence. This indicates that if harvest activity can be delayed until after senescence, some of the N, P and K will relocate back into the root system and will minimize the need for their replacement (Parrish and Fike, 2005; Mooney et al, 2010). To date, though, conventional economic methods commonly used to determine the most economical harvest time and corresponding rates of fertilizer (Mulkey et al., 2006; Lemus et al., 2008; Haque et al., 2009; Aravindhakshan et al., 2011) do not consider the potential agronomic problems (benefits) associated with soil nutrient mining (remobilization) that are associated with producing switchgrass feedstock.

There is published research that reports a vertically integrated switchgrass supply system would be more economical compared to an individual farmer-based system because the benefits from spreading the fixed costs of expensive harvest machinery over a wide harvest window (i.e., July through March) is expected to significantly outweigh the losses in revenue expected from yield reductions from multiple one-cut harvests spread over thousands of acres over the same window (Epplin et al, 2007; Haque and Epplin, 2010). However, in either supply system (i.e., farmer-based or vertically integrated), substantial nutrient mining is expected to be the result. In contrast, multiple studies have reported that a one-cut winter system (December) is preferred to the two-cut harvest systems mentioned above (Mulkey et al., 2006; Haque et al., 2009; Aravindhakshan et al., 2011). Guretzky et al. (2011) reported that a two-cut harvest system (July and December) produced more yield than a one-cut winter system. However, in the case of the one-cut system, no attempts have been made to account for the potential economic benefits associated with the plant's biological ability to remobilized nutrients back to the root zone for which it makes available for use in the following year.

The objectives of this study were to (1) determine the long-term, economically sustainable harvest system and corresponding rates of N, $P_2O_5$, and $K_2O$ for producing switchgrass feedstock in the southern Great Plains; and (2) compare and contrast the difference in benefits and costs associated with the traditional and sustainable economic approaches used to determine the best harvest system and corresponding nutrient rates; and (3) determine how sensitive the results are to assumptions about prices of fertilizers, prices of feedstock and yields associated with the sustainable economic approach. This research is important in order to help production scientists develop best management practices that will help preserve the fragile nutrient base already present in the soils in the region. Moreover, these best management practices will serve to reduce the risk associated with investor concerns about the potential failure of farms to provide a locally produced long-term, steady supply of feedstock over the full necessary life of the investment required for building and operating a large-scale biorefinery. Although, the sustainable analytical approach used in this research only determine economically sustainable harvest and nutrient management strategy for the production of switchgrass, this same technique could be applied to other crop for the same purpose.

## 2. Theoretical framework

A rational farmer wants to know how best to manage the system of harvesting activities (i.e., when to cut, rake, bale, and stage feedstock) and how best to manage N, P and K nutrients for that system in order to obtain the long-term, economically sustainable success of the feedstock production enterprise on his farm. Therefore, enterprise budgeting techniques were used under the expected profit-maximization framework to analyze and compare both the shortterm unsustainable and long-term sustainable profitability of applying N, P and K nutrients on two independent harvest systems. The switchgrass farmer was presumed to be risk-neutral regarding the objective of maximizing his expected net returns, and so the producer's objective function can be expressed mathematically as:

$$\max_{H,N,P,K} E(NR) = \max\{ \rho_b E[Y(H,N,P,K)] - r^N N - r^p P - r^k K - r^a - r^h - r^b Y(H,N,P,K)$$

$$- \mathrm{r}^x X - FC,$$

Subject to:

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

$H \in \{1 = WNTR, 2 = SMWNTR\}$;

$N, P, K, X, FC \geq 0$;

$r^N, r^N, r^K, r^a, r^h, r^b, r^x \geq 0,$ (1).

where $\mathrm{E}(NR)$ refers to the expected net returns ($ ha$^{-1}$ yr$^{-1}$), $\rho_b$ is the price of switchgrass feedstock ($ Mg$^{-1}$), $Y(H,N,P,K)$ is feedstock yield (Mg ha$^{-1}$ yr$^{-1}$) and is a function of the levels nitrogen (*N*), phosphorus (*P*), and potassium (*K*) fertilizers (kg ha$^{-1}$ yr$^{-1}$) for a given harvest system *H* (either a winter only system (WNTR) or a summer and winter (SMWNTR) system); $r^N$, $r^P$, and $r^K$ are the price of *N*, *P* and *K*, respectively; $r^a$ is the custom application rate for applying *N*, *P* and *K* fertilizers ($ ha$^{-1}$); $r^h$ is a vector of custom rates for mowing, raking, and staging feedstock ($ ha$^{-1}$); $r^b$ is the custom rate for baling switchgrass feedstock ($ Mg$^{-1}$); $r^x$ is a vector of prices that corresponds to the vector *X* containing non-fertilizer, non-harvest activity inputs, such as pesticide, pesticide application, and interest on operating capital; and $FC$ represents fixed cost associated with the annual prorated cost of switchgrass establishment and land rent. It is noteworthy to point out that economic theory suggests that for the risk-neutral producer, the expected net return from producing switchgrass feedstock must be greater than the current level of profitability that he typically earns from the crop or crop mix that he currently producing with his land, labor, management, and overhead resources.

## 3. Data

Data were collected in four production seasons (2008-2011) from two field experiments conducted on established stands of switchgrass (var. ‘Alamo’). The first site was located at Varner Farms (VF) near the community of Frederick in Tillman County, OK (34º23´ N, 98º85´ W) and the second at the Noble Foundation’s Red River Research Farm (RRRF) located near the community of Burneyville in Love County, OK (33º89´ N, 97º29´ W). The experimental design was a randomized complete block with four replications. The two harvest systems included (1) a single cut in the winter after a hard freeze, after plant senescence (WNTR); and (2) a two cut system that included a summer cut in July at the time of plant maturity, followed by a second cut of the regrowth in the winter (December) after a hard freeze, after plant senescence (SMWNTR). Each study site and harvest system received 0, 45, 90, 135, 179 and 224 kg $ha^{-1}$ $yr^{-1}$ of N in the form of urea (46-0-0), 67 kg $ha^{-1}$ $yr^{-1}$ of phosphorus in the form of $P_2O_5$ (0-46-0), and 135 kg $ha^{-1}$ $yr^{-1}$ of potassium in the form of $K_2O$ (0-0-60).

During the establishment year (2007), soil samples were collected from both locations to conduct tests in order to ensure adequate level of pH, N, P and K. At the RRRF site, a single application (2.34 L $h^{-1}$) of Glyphosate [N-(phosphonomethyl) glycine] was applied across the plots to suppress all grassy weeds prior to establishment of switchgrass. Seedbeds were prepared by discing twice followed by cultivated using a field cultivator. Switchgrass was planted in May at both locations into a clean-tilled prepared seedbed using a SS-series Brillion seeder (Brillion farm equipment, Brillion, WI, USA) at 5.6 kg PLS seed $ha^{-1}$. A single application (3.51 L $h^{-1}$) of 2,4-D Amine (2,4-dichlorophenoxyacetic acid, dimethyl amine) was applied on 19 July, 2007 at the RRRF site to control broadleaf weeds.  During the establishment year no fertilizer was applied as switchgrass, and none of the plots were harvested in the establishment year as recommended for stand longevity (Lawrence et al. 2006).  All plots at both sites were harvested in 2008, 2009, 2010, and 2011 using a custom harvester.

Sub-samples of the harvested switchgrass were collected to calculate dry matter yield and nutrient concentration measures for crude protein (CP), P and K.  Following drying at 60°C, samples were ground to pass a < 1 mm screen using a Wiley Mill (Thomas Scientific, Swedesboro, NJ). Ground material was analyzed for CP, P and K using the Foss 6500 near infra-red reflectance spectroscopy (NIRS) instrument. The samples were scanned using Foss ISI Scan software and prediction equations developed by the NIRS Forage and Feed Testing Consortium (Hillsboro, WI). The CP concentration mean, standard error of validation, and $r^2$ for the equation used were: 19.9 g $kg^{-1}$, 1.3 g $kg^{-1}$ and 0.98, respectively. The P mean, standard error of validation, and $r^2$ for the equation used were: 1.9 g $kg^{-1}$, 0.4 g $kg^{-1}$ and 0.73, respectively. The K mean, standard error of validation, and $r^2$ for the equation used were: 16 g $kg^{-1}$, 2.8 g $kg^{-1}$ and 0.85, respectively. These equations were then used to predict CP, P, and K for all samples. Concentrations of N removed by the plants were then calculated from CP by dividing each observation of CP by 6.25. Amounts of P and K removed by biomass were converted to $P_2O_5$ and $K_2O$ kg $ha^{-1}$ equivalents.  Comprehensive details regarding the growing conditions and agronomic relationships between feedstock yield response to N, P and K nutrients and concentrations for the alternative harvest systems for each location and year are reported in Guretzky et al. (2011).

Table 1 reports the nutrient levels applied via agronomic treatments, average nutrient concentrations of N, $P_2O_5$, and $K_2O$, the average level of nutrients either mined (if negative) or remobilized (if positive) from the soil, and the average corresponding yields for each harvest system. It is noteworthy to point out that feedstock harvested from the SMWNTR system had the greatest yields compared to the WNTR system; however, this system also realized the greatest levels of N, $P_2O_5$, and $K_2O$ actually removed (mined) by the plants from the soil.

## 4. Methods and procedures

Enterprise budgeting techniques were used to determine costs and net returns for two approaches. Econometric methods were used to estimate effects of N, P and K fertilizers on yield for the two approaches (models). Model 1 represents the conventional economic approach that uses the fertilizer treatments applied (N, $P_2O_5$ and $K_2O$) in the experiment. Model 2 reflects the long-term sustainability approach and uses the nutrient concentration measures (N, P and K removed by harvested biomass) calculated from the forage samples collected in the study. For analysis purpose, nutrient concentration measures (N, P and K removal) were converted to N, $P_2O_5$ and $K_2O$ (kg $ha^{-1}$) equivalents. It is important to note that these data provide insight regarding how the plants consumed nutrient they had available to them either through synthetic sources given to them by application of treatments or through sources available from the soil or through the atmosphere. These concentration measures do not, however, reveal how efficiently they converted nutrients into forage or feedstock.

### *4.1. Economics*

Standard enterprise budgeting techniques (AAEA 2000) were used to estimate the economic net returns described in equation 1 for two separate economic approaches. For this study, full detailed were developed, accounting for all the costs of production, including the costs of establishment of switchgrass stands. The only costs that were not considered in the analysis were associated with the owner's labor and management, and overhead. These were not considered because they tend to differ depending on farm size and location within the region. The first economic approach (defined as Model 1) represents the conventional economic approach used by Epplin et al. 2011 to determine the most profitable harvest system and corresponding levels of N, P and K fertilizers. The second economic approach (Model 2) reflects an alternative approach that uses the plant uptake data (i.e., the N, $P_2O_5$ and $K_2O$ concentration equivalents determined via forage analysis) to determine the long-term, economically sustainable harvest system and corresponding best management levels of N, P and K. The budgets included the prorated annual establishment costs as well as annual costs of annual stand maintenance and harvesting activities. The cost of field activities including discing, cultivating, seedbed preparation, herbicide application and harvesting were calculated using state average custom operation rates (Doye and Sahs 2008). The custom rates of \$23.90 $ha^{-1}$ and \$19.15 $ha^{-1}$ were used for discing and cultivating, respectively. A switchgrass seed price of \$33.00 $kg^{-1}$ was used. Estimated establishment costs were amortized over 10 years at a rate of 6.25 percent.

Budgeted cost of annual maintenance of switchgrass after the establishment year included the cost of fertilizers (N, $P_2O_5$ and $K_2O$), costs of harvesting activities (mowing, raking, baling and staging), pesticide and pesticide application, operating capital, and land rental. Costs of mowing, raking and staging were estimated on a per hectare basis, but the cost of baling (large square bales) was a function of total yield of feedstock. Custom rates of \$24.98 $ha^{-1}$, \$9.59 $ha^{-1}$, \$36.18 $ha^{-1}$ and \$11.12 $ha^{-1}$ were used for mowing, raking, bailing and hauling and stacking, respectively (Doye and Sahs, 2010). The land rental rate was assumed to be \$124 $ha^{-1}$ $yr^{-1}$.

Nutrients removed by harvested feedstock were determined after harvest, and as a result nutrient cost adjustments for model 2 were made by calculating the difference between the fertilizer treatments applied and nutrient concentration measures (Table 1). A positive difference implies that nutrients were removed (mined) from the soil by the plants, and a negative difference implies that nutrients were remobilized back to the root zone. For example, for the WNTR system that received 40 kg $ha^{-1}$ N, 67 kg $ha^{-1}$ of $P_2O_5$ and 135 kg $ha^{-1}$ of $K_2O$, switchgrass plants actually removed 49, 18 and 35 kg $ha^{-1}$ of N, $P_2O_5$ and $K_2O$, respectively (table 2). For the case of N, the plants, on average, actually mined 9 (49 kg – 40 kg) kg $ha^{-1}$ from the ground since only 40 kg of N $ha^{-1}$ $yr^{-1}$ was applied during field experiment. However, there was excess application of $P_2O_5$ and $K_2O$, since plant only used 18 and 35 kg $ha^{-1}$, respectively. Under the conventional approach, cost of N was under estimated and costs of $P_2O_5$ and $K_2O$ were over estimated. So for the sustainable economic approach (Model 2), cost of N, $P_2O_5$ and $K_2O$ was adjusted according to plant's actual nutrient requirement. The same adjustments were administered for both harvest systems for each level of N, $P_2O_5$ and $K_2O$.

### *4.2. Sensitivity analysis*

To account for the lack of an established market for switchgrass feedstock and unpredictable volatility in fertilizer prices in the region, a number of feedstock and fertilizer price scenarios were analyzed via sensitivity analysis. A sensitivity analysis was also conducted to determine how the relative economic results are expected to change between the two economic approaches for relatively favorable (high biomass/low N price) and non-favorable (low biomass/high N price) biomass and N price scenarios.

Furthermore, it was assumed that feedstock yields obtained for each of the N application treatments (0, 45, 90, 135, 179, and 224 kg of N $ha^{-1}$ $yr^{-1}$) used to determine the most economic system for the conventional approach are the same as for the nutrient concentration measures for N, P and K under sustainable approach (table 2). For example, the application of 0, 67, 135 kg ha$^{-1}$ of N, $P_2O_5$ and $K_2O$ realized a feedstock yield of 10.3 Mg ha$^{-1}$. The nutrient concentration equivalents associated with these treatments were 33, 20 and 39 kg of N, $P_2O_5$ and $K_2O$, respectively. It was also assumed in the base-case scenario that in the case of long-term sustainability (Model 2), 100% of the nutrients not used by the plants and remobilization to the root zone will be available for switchgrass plants to re-use in the following year. However, this assumption may not be fully plausible because some of the nutrients that are remobilized to the root zone are likely used during the following year to boost shoot growth and some of these nutrients may be lost through leaching or volatilization (Lemus, Parrish and Abaye 2008). To address these issues, sensitivity analyses were conducted to determine how robust expected net profitability was for variations in these assumptions. First, instead of a 100% yield obtained from the nutrient concentration equivalents resulting from the forage analysis, we analyzed what the results would be assuming that plants only realized 75% and 50% of the yields obtained from the N, P and K treatments analyzed in Model 1. And second, instead of the assumption that 100% of the N, P and K concentration equivalents remobilized to the root zone and made available by the plant for reuse in the following year, we analyzed what the results would be for cases where only 50% and only 25% of the nutrients were made available by the plants for reuse in the following year. This will give us an idea about how sensitive our economic results are to the remobilization question.

### *4.3.Econometric analyses*

Econometric techniques were used to estimate the effects of harvest systems and N, P and K nutrient levels on feedstock yield for the conventional and sustainability approaches (Modle 1 and Model 2). Three functional forms (Linear response (LRF), quadratic response (QR), and a linear response plateau (LRP)) were specified for both economic models. The most suitable functional form was selected based on the Likelihood Dominance Criteria (LDC) and Likelihood Ratio (LR) tests. The Likelihood Dominance Criterion (LDC) was used to choose between the nonnested QR and LRP form (Pollak and Wales 1991). The most suitable functional form between the nested function (i.e., LRF and QR, or between LRF and LRP) was chosen based on the results of a Likelihood Ratio (LR) test (Greene 2008). The LRF, QR, and LRP response functions were estimated using the NLMIXED procedure in SAS (Little et al. 1996; SAS Inst. 2008). Separate response functions were estimated for the WNTR and SMWNTR system because each harvest system was considered to be independent and nutrients requirements of switchgrass feedstock only vary depending on the time of harvest (McLaughlin and Kszos 2005). Previous studies reported that data of this nature (i.e. yield responses to varying levels of fertilizers) face issues associated with heteroskedastic (unequal variances) variances (Bharat, Smith and Favret, 2006). To test the hypothesis of equal variance (variances are homoscedastic across N treatments), the LR test was used (Greene 2008). Based on the LR test, the null hypothesis of homoscedastic variance (i.e., equal variances) across fertilizer rates was rejected at a 95% level of confidence (LR = 46.8; $X^2$=3.84; j=1). As a result, the yield response to N function was estimated by allowing the error terms in the model to vary by fertilizer rates (Boyer, 2011).

*4.3.1. Conventional economic approach*

Under the conventional economic approach (Model 1), the actual fertilizer treatments (N, $P_2O_5$, and $K_2O$) applied in the field experiments were used to determine yield response to nutrient response separately for each harvest system. Nitrogen is considered to be the only continuous variable under conventional approach since the level of $P_2O_5$ and $K_2O$ are fixed at 67 kg and 135 kg $ha^{-1}$ $yr^{-1,}$ respectively, under this system. The three functional forms that were used to estimate the effects of treatment on yields are specified as follows:

LR: $Y_{itj} = \beta_0 + \beta_1 N_{itj} + \upsilon_t + \varepsilon_{itj}$ (2).

QR: $Y_{itj} = \beta_0 + \beta_1 N_{itj} + \beta_2 N_{itj}^2 + \upsilon_t + \varepsilon_{itj}$ (3).

LRP: $Y_{itj} = \min(\beta_0 + \beta_1 N_{itj},\ y_m) + \upsilon_t + \varepsilon_{itj}$ (4).

where $Y_{itj}$ is the switchgrass yield (Mg $ha^{-1}$) on *i*th plot in site-year *t* for each treatment *j*, $\beta_0$ is the yield intercept, $\beta_1$ and $\beta_2$ are the slope parameters to be estimated, $N_{itj}$ is the level of nitrogen application on feedstock for each treatment *j* where *j* = 0, 45, 90, 135, 179 and 224 kg $ha^{-1}$ $yr^{-1}$ on plot *i* in site-year *t*, $y_m$ is the average plateau yield, $\upsilon_t$ is random error term used to capture the site-year effect, and $\varepsilon_{itj}$ is the usual error term. The random errors $\upsilon_t$ and $\varepsilon_{itj}$ are assumed to be independent and normally distributed with means of zero, and variances $\sigma_\upsilon^2$ and $\sigma_{itj}^2$, respectively, and $\sigma_\upsilon^2$ and $\sigma_{itj}^2$.

*4.2.2. Sustainable economic approach*

Under the sustainable economic approach (Model 2), nutrients concentration equivalents that reveal how much N, $P_2O_5$, and $K_2O$ nutrients were removed from the soil by the plants were used to determine the economically sustainable harvest system and corresponding nutrient management strategy. Scatter plots revealed the existence of linear relationship between feedstock yield and nutrient concentration equivalents for much N, $P_2O_5$, and $K_2O$. Unfortunately for a linear relationship such as this, it is not possible to determine the optimal level of nutrient application because the multivariate yield response function is not twice differentiable. Therefore, a standard analysis of variance (ANOVA) approach was used to compare the mean feedstock yield between levels of nutrient concentration equivalents (Littell et al. 1996; SAS Inst. 2008). Harvest system and the level of nutrient concentration equivalent was treated as fixed effects in the random-effects mixed ANOVA model, and site-year was treated as a random effect (Biermacher et al. 2009; Tembo, Brorsen and Epplin 2008).

This econometric approach was conducted in two steps. First, mean net return for each plot was estimated against harvest system and the average level of nutrient equivalents for N, $P_2O_5$, and $K_2O$ in order to determine the most economically sustainable harvest system (WNTR or SMWNTR). Then, once the economically sustainable harvest system was identified using Fisher's protected F test, then least significant difference (LSD) testing was used to scrutinize between and identify the most economically sustainable levels of N, $P_2O_5$, and $K_2O$.

## *5.* Results and discussion

### *5.1. Conventional economic approach*

#### *5.1.1. Econometric results*

The LDC and LR tests revealed that the Linear Response Plateau (LRP) functional form provided for the best statistical fit of the data for the WNTR system while the quadratic response (QR) form fit the data best for the SMWNT system. Parameter estimates for both systems are presented in Table 2. All mean parameters and variance terms were statistically significant at a 1%, 5%, or 10% level of confidence. The LRP estimates showed that plots represented by the WNTR system achieved a plateau yield of 14.7 Mg $ha^{-1}$ $yr^{-1}$ with an annual application of 112 kg N $ha^{-1}$. Conversely, the optimal economic yield of the SMWNTR system was much higher at 19.5 Mg $ha^{-1}$ and required 225 kg N $ha^{-1}$ $yr^{-1}$, substantially greater than the WNTR system.

#### *5.1.2. Economic results*

Optimal N levels, expected yields and expected net returns for a number of various prices for feedstock and N for each harvest system are reported in Table 3. For the base-case price scenario (i.e., a feedstock price of \$83 $Mg^{-1}$ and an N price of \$1.19 $kg^{-1}$), the results for the

WNTR system suggests that producers should apply 111, 67, and 135 kg $ha^{-1}$ of N, $P_2O_5$, and $K_2O$, respectively, and will produce 14.7 Mg $ha^{-1}$ and earn a net return of \$200 $ha^{-1}$. Notice that with the QR function representing the SMWNTR system, the profit-maximizing levels of yield and N vary depending on the assumed price of feedstock and N. However this is not the case for the LRP; that is, the yield maximizing level of N is the profit-maximizing level so long as the margin value product (MVP) of N is greater than the marginal input cost (MIC) of N. In contrast, for the same base-case price scenario, our results show that for the SMWNTR system, producers should apply 199, 67 and 135 kg $ha^{-1}$ of N, $P_2O_5$ and $K_2O$, respectively, and will generate 19.4 Mg $ha^{-1}$ of feedstock and earn \$313 $ha^{-1}$. The results suggests that producers would be better off economically by harvesting switchgrass twice per growing season with the SMWNTR system as opposed to only once after a hard freeze, after plant senescence with the WNTR system. In addition, the results show that for a farm-gate feedstock price of 55 $Mg^{-1}$ that average net returns for both harvest systems were negative, even for relatively low fertilizer prices. This indicates that producer in this region would not be willing to produce switchgrass feedstock on their farms.

### *5.2. Sustainable economic approach*

The expected net returns for three feedstock prices (\$55, \$83, and \$110) and three N prices (\$0.90, \$1.19, and \$2.20) for the WNTR and SMWNTR harvest systems calculated using the sustainable economic approach are reported in Table 5. Notice for the feedstock price equal to \$55 $Mg^{-1}$, the expected net return for both harvest systems are negative. However, the expected net return for the WNTR system is greater than those of the SMWNTR system for a feedstock price of \$83 $ha^{-1}$, and for this scenario the cost of nutrients is lower for the WNTR system compared to the SMWNTR system. This is due to a greater concentration of nutrients in the feedstock that was harvested prior to plant senescence, which is consistent with other published findings (Ball, Hoveland, and Lacefield 2002; Lemus, Parrish, and Wolfe 2009). For a base biomass price of \$83 $Mg^{-1}$ and N price of \$1.19 $kg^{-1}$ the expected net return was \$341 and \$55 $ha^{-1}$ for the WNTR and SMWNTR systems, respectively. For this price scenario, a producer can expect lose \$286 of net return with the SMWNTR system. This is certainly in direct contrast to what was found using the conventional economic approach (Model 1). Recall that for Model 1, the most economical system for the base-case price scenario was the SMWNTR system.

As winter harvest is the most profitable harvest system among two harvest systems (table 5), the most economical sustainable N, $P_2O_5$, and $K_2O$ rates that maximizes producer's net return were determined only for winter harvest system. Table 6 reported expected net returns (\$ $ha^{-1}$) of switchgrass biomass from ANOVA model of winter harvest at various biomass/N price combinations for six sustainable N, $P_2O_5$, and $K_2O$ rates. Net returns were greater with an annual application of 84, 28 and 50 kg of N, $P_2O_5$ and $K_2O$ $ha^{-1}$ $yr^{-1}$ compared to all other level of nutrients for a biomass price of \$83 $ha^{-1}$ and above for any combinations of N price. For a biomass price of \$83 $Mg^{-1}$ and above and N price of \$1.19 $kg^{-1}$, producer will achieve \$392 of net returns $ha^{-1}$ with an annual application of 84, 28 and 50 kg of N, $P_2O_5$ and $K_2O$ $ha^{-1}$ $yr^{-1}$, respectively. As biomass price falls from \$83 $Mg^{-1}$ to \$55 $Mg^{-1}$, the expected net returns are negative.

*5.2.1 Comparison of results between model 1 (sustainable) and model 2 (conventional)*

Table 7 reports comparisons of model 1 (unsustainable approach) and model 2 (sustainable approach) for a range of (favorable, base, unfavorable) biomass and N price scenarios. For the base case scenario where the farm-gate price of feedstock is \$83 $Mg^{-1}$ and price of N is \$1.19 $kg^{-1}$, results show that for the conventional economic approach (Model 1) farmers would maximize expected net return with the two-cut system, applying 199, 67 and 135 kg of N, $P_2O_5$ and $K_2O$ ha$^{-1}$ yr$^{-1}$. For this system, producers are expected to yield 19.4 Mg ha$^{-1}$ and generate $313 of net return ha$^{-1}$. Conversely, the economically sustainable solution (Model 2) was to harvest only once in December, and apply 84, 28 and 50 kg of N, $P_2O_5$ and $K_2O$ ha$^{-1}$ yr$^{-1}$, respectively. Under this system, farmers can expect to harvest 15.0 Mg of biomass and receive $392 of net return ha$^{-1}$. Results show that producers will receive $79 ha$^{-1}$ greater net return under long-term sustainable approach compared to unsustainable approach.

For an unfavorable market price scenario where the farm-gate price of biomass was relatively low ($55 Mg$^{-1}$) and price for N was relatively high ($2.20 kg$^{-1}$), average net returns from both approaches are negative. Under this situation, producers would not be willing to produce switchgrass biomass on their farms. In contrast, , estimated net return for a favorable market price scenario (high biomass/low N price) was greater for the conventional economic approach (Model 1), where farmers would maximize expected net return with the two-cut system, applying 215, 67 and 135 kg of N, $P_2O_5$ and $K_2O$ ha$^{-1}$ yr$^{-1}$. For this system, producers will generate $901 of net return ha$^{-1}$. Conversely, the economically sustainable solution (Model 2) was to harvest only once in December, and farmers can expect to receive $831 of net return ha$^{-1}$. Results show that economic sustainability will require farmers to forego $71 of profit ha$^{-1}$, something they may not be inclined to do. The $71 ha$^{-1}$ difference in net return between the two models reflects the economic trade-off between short-run, unsustainable profitability and long-term economic sustainability. Overall, one can say that the result is sensitive to the prices of biomass and N.

*5.2.1 Results of sensitivity analysis on yield proportion and recycled nutrient*

Tables 8-11 report expected net returns of switchgrass biomass estimated from sensitivity analysis under sustainable approach for proportional change in yield and change in recycled nutrient availability for re-use in the following year. In addition, table 12 reports comparison between unsustainable model and sustainable models for all four case scenarios. Results show that for all four cases of sustainable approach, it appears that producers will be better off by harvesting switchgrass in winter compared to summer/winter under all biomass and N price combinations. But results also show that if winter system yielded only 75%, economic sustainability, it will require farmers to forego \$125 of profit $ha^{-1}$, something they may not be inclined to do. In addition, producers will face net loss of \$10 and would not consider long-term sustainable approach when switchgrass produces only 50% of yield for winter harvest system. Similar results were found under case III and case IV.

## 6. Conclusions and limitations

Conventional economic methods commonly used to determine the most economical harvest time and corresponding rates of fertilizer do not consider the potential agronomic problems (benefits) associated with soil nutrient mining (remobilization) that are associated with producing switchgrass as a bioenergy feedstock. The objectives of this study were to (1) determine the long-term, economically sustainable harvest system and corresponding rates of N, $P_2O_5$, and $K_2O$ for producing switchgrass feedstock in the southern Great Plains; and (2) compare and contrast the difference in benefits and costs associated with the traditional and sustainable economic approaches used to determine the best harvest system and corresponding nutrient rates; and (3) determine how sensitive the results are to assumptions about prices of fertilizers, prices of feedstock and yields associated with the sustainable economic approach. We found that for feedstock prices ranging from \$55 $Mg^{-1}$ to \$110 $Mg^{-1}$ and N price ranging from

\$0.90 $kg^{-1}$ to \$2.20 $kg^{-1}$ it is more economically sustainable to harvest switchgrass only once $yr^{-1}$ in the winter after a hard freeze, after plant senescence compared to harvesting feedstock in the summer at plant maturity and again in the winter after a hard freeze.

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**Table 1 – Levels of N, P and K treatments, concentrations, and nutrients mined or remobilized, and feedstock yield by harvest system.**

| Nutrient treatment rates (kg ha$^{-1}$ yr$^{-1}$) | | | Nutrients concentration levels† (kg ha$^{-1}$ yr$^{-1}$) | | | Nutrients levels mined/remobilized‡ (kg ha$^{-1}$ yr$^{-1}$) | | | Feedstock yield (Mg ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| N | P | K | N | P | K | N | P | K | |
| | | | | WNTR system | | | | | |
| 0 | 67 | 135 | 33 (33)§ | 16 (10) | 31 (37) | -33 | 52 | 103 | 10.3 |
| 45 | 67 | 135 | 55 (41) | 20 (11) | 39 (38) | -10 | 47 | 95 | 12.4 |
| 90 | 67 | 135 | 68 (50) | 25 (13) | 44 (47) | 21 | 43 | 91 | 14.1 |
| 135 | 67 | 135 | 84 (58) | 28 (18) | 50 (48) | 50 | 39 | 84 | 15.0 |
| 179 | 67 | 135 | 101 (57) | 29 (16) | 43 (43) | 78 | 38 | 92 | 15.0 |
| 224 | 67 | 135 | 105 (60) | 30 (17) | 48 (48) | 119 | 37 | 86 | 14.7 |
| | | | | SMWNTR system | | | | | |
| 0 | 67 | 135 | 73 (54) | 30 (17) | 120 (79) | -73 | 37 | 15 | 9.5 |
| 45 | 67 | 135 | 106 (65) | 41 (20) | 170 (91) | -62 | 26 | -36 | 12.8 |
| 90 | 67 | 135 | 154 (77) | 56 (27) | 236 (120) | -64 | 11 | -102 | 16.4 |
| 135 | 67 | 135 | 185 (86) | 61 (32) | 256 (135) | -50 | 7 | -121 | 17.0 |
| 179 | 67 | 135 | 220 (107) | 71 (37) | 309 (163) | -40 | -3 | -175 | 20.4 |
| 224 | 67 | 135 | 229 (105) | 69 (36) | 286 (145) | -4 | -2 | -151 | 19.3 |

† Nutrient concentration levels given by standard forage (NIRS) analysis. These represent levels of nutrients that were removed by switchgrass plants. Nutrients are in the form of N, $P_2O_5$ and $K_2O$.

‡Calculated as the difference between nutrient applied and nutrient concentration level. A negative value implies the nutrient was mined and a positive value implies the nutrient was remobilized to the root zone of the plant.

§Numbers in parenthesis are stand deviations.

**Table 2 - Switchgrass feedstock yield response to N for the linear response plateau (LRP) form for the WNTR system and the quadratic (QR) form for the SMWNTR system.**

| Variables[a] | WNTR system LRP | SMWNTR system Quadratic |
|---|---|---|
| Intercept | 10.1581*** | 9.4558*** |
| | (1.6687) [b] | (1.7925) |
| N rate | 0.04098** | 0.08855*** |
| | (0.007656) | (0.01473) |
| $N^2$ | | -0.00019* |
| | | (0.000084) |
| Maximum yield, Mg $ha^{-1}$ $yr^{-1}$ | ----- | 19.7408 |
| Plateau yield, Mg $ha^{-1}$ $yr^{-1}$ | 14.6981*** | ----- |
| | (1.6677) | |
| Level of N at maximum yield, kg $ha^{-1}$ | 110.78 | 225 |
| Site-year error variance | 21.0022* | 33.1219* |
| | (11.4691) | (12.5112) |
| Intercept of the error variance | 1.7345*** | 2.2032*** |
| | (0.2033) | (0.1269) |
| Slope of the error variance | 0.005394** | 0.008887*** |
| | (0.001540) | (0.001453) |
| -2 Log likelihood | 1000.1 | 1671.6 |

* Statistically significant at 10% level.
** Statistically significant at 5% level.
*** Statistically significant at 1% level.
[a] The dependent variable is switchgrass feedstock yield (Mg $ha^{-1}$).
[b] Numbers in parentheses are standard errors.

**Table 3 - Optimum level of N, expected yield and expected net return by harvest system calculated using the conventional economic approach for alternative farm-gate feedstock and N price scenarios.**

| Feedstock price ($ $Mg^{-1}$) | Price of nitrogen ($ $kg^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | WNTR system[a] | | | SMWNTR system | | |
| | 0.90 | 1.19 | 2.20 | 0.90 | 1.19 | 2.20 |
| | Optimum level of N (kg $ha^{-1}$ $yr^{-1}$) | | | | | |
| 55 | 111 | 0 | 0 | 193 | 180 | 131 |
| 83 | 111 | 111 | 0 | 208 | 199 | 166 |
| 110 | 111 | 111 | 111 | 215 | 208 | 184 |
| | Expected yield (Mg $ha^{-1}$) | | | | | |
| 55 | 10.2 | 10.2 | 10.2 | 19.3 | 19.1 | 17.8 |
| 83 | 10.2 | 14.7 | 10.2 | 19.5 | 19.4 | 18.9 |
| 110 | 10.2 | 14.7 | 14.7 | 19.5 | 19.5 | 19.2 |
| | Expected net return ($ $ha^{-1}$) | | | | | |
| 55 | -171 | -190 | -190 | -159 | -206 | -318 |
| 83 | 234 | 200 | 90 | 370 | 313 | 153 |
| 110 | 639 | 605 | 489 | 901 | 845 | 657 |

[a] The linear response plateau (LRP) functional form was estimated for WNTR system and a quadratic response (QR functional form was estimated for the SMWNTR system.

**Table 4 - Net returns of switchgrass feedstock by harvest systems at various feedstock and N price scenarios calculated with the sustainable economic approach.**

| Feedstock price ($ Mg$^{-1}$) | N price ($ kg$^{-1}$) | Harvest system[a] | |
|---|---|---|---|
| | | WNTR | SMWNTR |
| 55 | 0.90 | -10a | -284b |
| 55 | 1.19 | -32a | -324b |
| 55 | 2.20 | -109a | -462b |
| 83 | 0.90 | 363a | 94b |
| 83 | 1.19 | 341a | 55b |
| 83 | 2.20 | 263a | -84b |
| 110 | 0.90 | 736a | 474b |
| 110 | 1.19 | 714a | 434b |
| 110 | 2.20 | 638a | 296b |

[a] Means within a row comparing harvest systems followed by a common letter are not significantly different at $P \leq 0.05$.

**Table 5 - Net returns ($ ha$^{-1}$) of switchgrass feedstock produced with the WNTR system under calculated using the sustainable economic approach for various feedstock and N prices scenarios.**

| Price of Feedstock ($ Mg$^{-1}$) | Sustainable N rate | Sustainable P rate | Sustainable K rate | Price of nitrogen ($ kg$^{-1}$) | | |
|---|---|---|---|---|---|---|
| | | (kg ha$^{-1}$ yr$^{-1}$) | | 0.90 | 1.19 | 2.20 |
| 55 | 33 | 16 | 31 | -23 [a] | -33 | -68a |
| | 55 | 20 | 39 | -16 | -33 | -91a |
| | 68 | 25 | 44 | 5 | -15 | -85a |
| | 84 | 28 | 50 | 4 | -21 | -110ab |
| | 101 | 29 | 43 | -6 | -35 | -139bc |
| | 105 | 30 | 48 | -25 | -56 | -167c |
| 83 | 33 | 16 | 31 | 260c | 250c | 216 |
| | 55 | 20 | 39 | 326c | 310bc | 252 |
| | 68 | 25 | 44 | 393ab | 373ab | 303 |
| | 84 | 28 | 50 | 418a | 392a | 304 |
| | 101 | 29 | 43 | 405ab | 376ab | 272 |
| | 105 | 30 | 48 | 379ab | 348ab | 237 |
| 110 | 33 | 16 | 31 | 543c | 534c | 499c |
| | 55 | 20 | 39 | 669bc | 652bc | 594bc |
| | 68 | 25 | 44 | 781ab | 761ab | 691ab |
| | 84 | 28 | 50 | 831a | 806a | 717a |
| | 101 | 29 | 43 | 816ab | 786ab | 682b |
| | 105 | 30 | 48 | 784a | 752a | 641b |

[a] Means given across N, P, and K rates for the same feedstock and N price scenario followed by a common letter are not significantly different at $P \leq 0.05$.

**Table 6-Net returns by harvest system calculated with the sustainable economic approach for alternative feedstock prices, nitrogen prices, and feedstock yield scenarios.**

| Price of feedstock ($ $Mg^{-1}$) | Price of nitrogen ($ $kg^{-1}$) | Harvest system | | | |
|---|---|---|---|---|---|
| | | WNTR | SMWNTR | WNTR | SMWNTR |
| | | 75% of yield scenario | | 50% of yield scenario | |
| 55 | 0.9 | -101a | -378b | -193a | -470b |
| 55 | 1.19 | -123a | -417b | -215a | -510b |
| 55 | 2.2 | -201a | -555b | -292a | -648b |
| 83 | 0.9 | 178a | 93b | -6a | -281b |
| 83 | 1.19 | 156a | 132b | -28a | -320b |
| 83 | 2.2 | 79a | -271b | -106a | -459b |
| 110 | 0.9 | 458a | 191b | 180a | -91b |
| 110 | 1.19 | 436a | 151b | 158a | -130b |
| 110 | 2.2 | 359a | 13b | 81a | -269b |

**Table 7- Net returns ($ ha$^{-1}$) of switchgrass feedstock for the WNTR system calculated using the sustainable economic approach for various feedstock, N prices and percent of yield scenarios.**

| | | | | 75% yield scenario | | | 50% yield scenario | | |
|---|---|---|---|---|---|---|---|---|---|
| Feedstock price ($ Mg$^{-1}$) | Sustainable level of N (kg ha$^{-1}$) | Sustainable level of $P_2O_5$ (kg ha$^{-1}$) | Sustainable Level of $K_2O$ (kg ha$^{-1}$) | Price of N ($ kg$^{-1}$) | | | | | |
| | | | | 0.90 | 1.19 | 2.20 | 0.90 | 1.19 | 2.20 |
| 55 | 33 | 16 | 31 | -92 | -102a | -137a | -162a | -172a | -206a |
| | 55 | 20 | 39 | -100 | -116ab | -174b | -184b | -200b | -258b |
| | 68 | 25 | 44 | -90 | -109ab | -179b | -185b | -204b | -274bc |
| | 84 | 28 | 50 | -97 | -122ab | -211bc | -198bc | -223bc | -312cd |
| | 101 | 29 | 43 | -106 | -135bc | -240cd | -206cd | -236cd | -340de |
| | 105 | 30 | 48 | -123 | -155c | -266d | -222d | -254d | -365e |
| 83 | 33 | 16 | 31 | 120a | 110c | 75c | -20 | -30 | -65a |
| | 55 | 20 | 39 | 157a | 141bc | 82bc | -12 | -29 | -87a |
| | 68 | 25 | 44 | 201ab | 181ab | 111a | 9 | -10 | -80a |
| | 84 | 28 | 50 | 213abc | 188a | 99a | 8 | -17 | -105ab |
| | 101 | 29 | 43 | 202bc | 173abc | 68ab | -1 | -31 | -135bc |
| | 105 | 30 | 48 | 180c | 148abc | 37a | -20 | -52 | -163c |
| 110 | 33 | 16 | 31 | 332c | 323c | 288c | 122c | 112c | 77 |
| | 55 | 20 | 39 | 414bc | 397bc | 339bc | 159bc | 142bc | 84 |
| | 68 | 25 | 44 | 492a | 472a | 402ab | 203a | 183ab | 114 |
| | 84 | 28 | 50 | 523a | 498a | 409a | 215a | 190a | 101 |
| | 101 | 29 | 43 | 510ab | 481ab | 376abc | 204abc | 175abc | 71 |
| | 105 | 30 | 48 | 483a | 451ab | 340abc | 182ab | 150abc | 39 |

[a] Means given across N, P, and K rates for the same biomass and N price and yield scenarios followed by a common letter are not significantly different at $P \leq 0.05$ by the least square means test.

**Table 8 - Net return by harvest system calculated using the sustainable economic approach for alternative feedstock, N price, and level of nutrient N remobilized for plant reuse scenarios.**

| Price of feedstock ($ $Mg^{-1}$) | Price of N ($ $kg^{-1}$) | Harvest system | | | |
|---|---|---|---|---|---|
| | | WNTR | SMWNTR | WNTR | SMWNTR |
| | | 50% remobilization of N | | 25% remobilization of N | |
| 55 | 0.90 | -50a | -296b | -62a | -298b |
| 55 | 1.19 | -79a | -337b | -95a | -340b |
| 55 | 2.20 | -183a | -481b | -212a | -487b |
| 83 | 0.90 | 323a | 83b | 311a | 81b |
| 83 | 1.19 | 294a | 43b | 278a | 39b |
| 83 | 2.20 | 190a | -102b | 161a | -107b |
| 110 | 0.90 | 696a | 462b | 684a | 460b |
| 110 | 1.19 | 667a | 422b | 651a | 419b |
| 110 | 2.20 | 563a | 278b | 534a | 272b |

[a] Means given across a row between harvest system for each of the feedstock and N price scenarios followed by a common letter are not significantly different at $P \leq 0.05$.

**Table 9 - Net returns ($ ha$^{-1}$) for feedstock for the WNTR system calculated using the sustainable economic approach for various feedstock, N price and percent of N remobilized for plant reused scenarios.**

| Price of feedstock ($ Mg$^{-1}$) | Sustainable N rate (kg ha$^{-1}$ yr$^{-1}$) | Sustainable P rate (kg ha$^{-1}$ yr$^{-1}$) | Sustainable K rate (kg ha$^{-1}$ yr$^{-1}$) | Price of N ($ kg$^{-1}$) 0.90, 50% remobilized of N | 1.19, 50% remobilized of N | 2.20, 50% remobilized of N | Price of N ($ kg$^{-1}$) 0.90, 25% remobilized of N | 1.19, 25% remobilized of N | 2.20, 25% remobilized of N |
|---|---|---|---|---|---|---|---|---|---|
| 55 | 33 | 16 | 31 | -202cd | -222b | -289b | -202bc | -222bc | -289a |
| | 55 | 20 | 39 | -156a | -181a | -271a | -158a | -184a | -276a |
| | 68 | 25 | 44 | -173ab | -209a | -338c | -178a | -216b | -350b |
| | 84 | 28 | 50 | -197bc | -242b | -404d | -205b | -254c | -425c |
| | 101 | 29 | 43 | -223de | -279c | -478e | -235cd | 295d | -208d |
| | 105 | 30 | 48 | -240e | -301c | -517f | -258d | -325e | -563e |
| 83 | 33 | 16 | 31 | 63c | 44b | -24c | 63b | 44b | -24c |
| | 55 | 20 | 39 | 192b | 166a | 77a | 190a | 164a | 72a |
| | 68 | 25 | 44 | 248ab | 212a | 83a | 243a | 205a | 71a |
| | 84 | 28 | 50 | 244ab | 198a | 36ab | 235a | 187a | 15ab |
| | 101 | 29 | 43 | 267a | 210a | 12bc | 254a | 194a | -18bc |
| | 105 | 30 | 48 | 229ab | 167a | -50c | 210a | 143a | -94d |
| 110 | 33 | 16 | 31 | 329c | 310c | 242b | 329c | 310c | 242c |
| | 55 | 20 | 39 | 539b | 514b | 424a | 537b | 511b | 420ab |
| | 68 | 25 | 44 | 670a | 633a | 504a | 665a | 627a | 492a |
| | 84 | 28 | 50 | 684a | 639a | 477a | 676a | 627a | 456ab |
| | 101 | 29 | 43 | 756a | 700a | 501a | 744a | 684a | 472ab |
| | 105 | 30 | 48 | 697a | 636a | 419a | 679a | 612a | 374b |

[a] Means given across N, P, and K rates for the same biomass and N price and case scenarios followed by a common letter are not significantly different at $P \leq 0.05$ by the least square means test.

**Table 10- Comparisons of agronomic and economic results from the conventional and sustainable economic approaches for a range (favorable to unfavorable) feedstock and N price scenarios.**

| Scenario/result variable | Conventional economic approach | Economic sustainable approach | Numerical difference | Percentage difference |
|---|---|---|---|---|
| Favorable scenario: High feedstock price, low N price | | | | |
| Optimal harvest system | SMWNTR | WNTR | - | - |
| Price of biomass ($ $Mg^{-1}$) | 55 | 55 | - | - |
| Price of N ($ $kg^{-1}$) | 2.20 | 2.20 | - | - |
| Level of N ($kg\ ha^{-1}\ yr^{-1}$) | 125 | 33 | -92 | 74% |
| Level of $P_2O_5$ ($kg\ ha^{-1}\ yr^{-1}$) | 67 | 16 | -51 | 77% |
| Level of $K_20$ ($kg\ ha^{-1}\ yr^{-1}$) | 182 | 31 | -151 | 83% |
| Biomass yield ($Mg\ ha^{-1}$) | 17.6 | 10.3 | -7 | 42% |
| Revenue ($ $ha^{-1}$) | 970 | 566 | -404 | 42% |
| Total Cost ($ $ha^{-1}$) | 1280 | 633 | -647 | 51% |
| Net Return ($ $ha^{-1}$) | -310 | -67 | 243 | 78% |
| Base case scenario | | | | |
| Optimal harvest system | SMWNTR | WNTR | - | - |
| Price of biomass ($ $Mg^{-1}$) | 83 | 83 | - | - |
| Price of N ($ $kg^{-1}$) | 1.19 | 1.19 | - | - |
| Level of N ($kg\ ha^{-1}\ yr^{-1}$) | 199 | 84 | -115 | -58% |
| Level of $P_2O_5$ ($kg\ ha^{-1}\ yr^{-1}$) | 67 | 28 | -39 | 58% |
| Level of $K_20$ ($kg\ ha^{-1}\ yr^{-1}$) | 135 | 50 | -85 | 63% |
| Biomass yield ($Mg\ ha^{-1}$) | 19.4 | 15.0 | -4 | 23% |
| Revenue ($ $ha^{-1}$) | 1604 | 1240 | -364 | 23% |
| Total Cost ($ $ha^{-1}$) | 1291 | 848 | -443 | 34% |
| Net Return ($ $ha^{-1}$) | 313 | 392 | 79 | 25% |
| Favorable scenario: high biomass price, low N price | | | | |
| Optimal harvest system | SMWNTR | WNTR | - | - |
| Price of biomass ($ $Mg^{-1}$) | 110 | 110 | - | - |
| Price of N ($ $kg^{-1}$) | 0.90 | 0.90 | - | - |
| Level of N ($kg\ ha^{-1}\ yr^{-1}$) | 215 | 84 | -131 | 61% |
| Level of $P_2O_5$ ($kg\ ha^{-1}\ yr^{-1}$) | 67 | 28 | -39 | 58% |
| Level of $K_20$ ($kg\ ha^{-1}\ yr^{-1}$) | 135 | 50 | -85 | 63% |
| Biomass yield ($Mg\ ha^{-1}$) | 19.5 | 15.0 | -5 | 23% |
| Revenue ($ $ha^{-1}$) | 2150 | 1653 | -496 | 23% |
| Total Cost ($ $ha^{-1}$) | 1248 | 823 | -426 | 34% |
| Net Return ($ $ha^{-1}$) | 901 | 831 | -71 | 8% |

**Table 11 – Sensitivity of results between conventional and sustainable economic approaches for various yield and nutrient remobilization scenarios.**

| Result variable | Conventional economic approach | Sustainable economic approach: 100% yield, 100% N remobilization | 75% yield | 50% yield | 50% remobilized N | 25% remobilized N |
|---|---|---|---|---|---|---|
| Economic harvest system | SMWNTR | WNTR | WNTR | WNTR | WNTR | WNTR |
| Price of feedstock ($ $Mg^{-1}$) | 83 | 83 | 83 | 83 | 83 | 83 |
| Price of N ($ $kg^{-1}$) | 1.19 | 1.19 | 1.19 | 1.19 | 1.19 | 1.19 |
| Level of N (kg $ha^{-1}$ $yr^{-1}$) | 199 | 84 | 84 | 68 | 68 | 68 |
| Level of $P_2O_5$ (kg $ha^{-1}$ $yr^{-1}$) | 67 | 28 | 28 | 25 | 25 | 25 |
| Level of $K_20$ (kg $ha^{-1}$ $yr^{-1}$) | 135 | 50 | 50 | 44 | 44 | 44 |
| Feedstock yield (Mg $ha^{-1}$) | 19.4 | 15.0 | 11.3 | 7.0 | 15.3 | 15.3 |
| Revenue ($ $ha^{-1}$) | 1604 | 1240 | 931 | 582 | 1262 | 1262 |
| Total Cost ($ $ha^{-1}$) | 1291 | 848 | 743 | 592 | 1050 | 1058 |
| Net Return/loss ($ $ha^{-1}$) | 313 | 392 | 188 | -10 | 212 | 205 |