Switchgrass Production in Marginal Environments: A Comparative Economic Analysis across Four West Tennessee Landscapes

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Abstract

Switchgrass (*Panicum virgatum* L.) has been identified as a model feedstock for the emerging biofuels industry. Its selection was based, in part, upon the observation that switchgrass can produce high yields in marginal production environments. This trait may become particularly valuable in coming years, as renewable fuel mandates begin to take effect and concerns over the food-versus-fuel debate increase. Relatively little research information exists about how management practices and production costs vary across different production environments. The objectives of this research were (a) to compare switchgrass yields as influenced by seeding rate and nitrogen fertilization rates in low-, intermediate-, and high-yielding switchgrass production environments, (b) to determine the economically optimal seeding rate and nitrogen fertilization rate for each environment, and (c) to calculate per-ton production costs. Experimental yield data from four locations were utilized for this study. Plots were seeded in 2004 with treatments of 2.5, 5.0, 7.5, 10.0, and 12.5 lbs/acre. Nitrogen was applied in subsequent intervals at 0, 60, 120 and 180 lbs/acre. For an expected stand lifespan of 10 years, production costs ranged from $45 per ton in a well drained level upland environment ideal for the production of row crops to $70 per ton in a marginal, poorly drained flood plain in which the switchgrass stand was slow to establish and which demonstrated lower overall yields.

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The Energy Independence and Security Act of 2007 will require 36 billion gallons of biofuel to be produced from renewable sources found within the United States by 2022. Just under 45% (16 billion gallons) of this is mandated to be derived from cellulosic biomass sources. To fulfill this mandate, De La Torre Ugarte, English, and Jensen (2007) estimate that up to 41.9 million acres (or 10% of the total U.S. agricultural land base) could become available for cellulosic biomass production depending on market conditions. Important questions surrounding this thrust include (a) what crops will be used to fulfill the cellulosic biomass mandate? and (b) in what settings and with what methods will these crops be cultivated?

In response to the first question, switchgrass (*Panicum virgatum* L.) has been identified as a model feedstock for the renewable biofuels industry (McLaughlin and Adam Kszos 2005). Switchgrass is a warm-season perennial grass native throughout the contiguous United States except the Pacific Northwest and parts of California (NRCS 2006). Cultivars are divided into lowland and upland ecotypes. Upland cultivars favor drier semi-arid climates, whereas lowland varieties are ideal for regions with more water availability (Hopkins et al. 1995; Stroup et al. 2003; Rinehart 2006; Porter 1966; Casler et al. 2004). Lowland varieties are well adapted to the southeastern United States and, in spite of lower quality soils compared to other regions, produce the highest dry matter yields due to longer growing days (Bransby 2008; Rinehart 2003).

This paper addresses the second question of where and how bioenergy crops will be produced. The selection of switchgrass as a dedicated energy crop was predicated, in part, upon the observation that it can produce high yields in marginal production environments, such as those with poor quality or highly erodable soils. It also requires few production inputs, is resistant to many pests and diseases, and does not require land to be continuously tilled. In 2002, the Farm Security and Rural Investment Act allowed for the harvesting of biomass on Conservation Reserve Program (CRP) land under specific conservation management guidelines and in exchange for a 25 percent reduction in annual rental payments (Mapemba et al. 2007). This development is promising as it may reduce much of the ethanol industry's competition for prime farmland traditionally planted with row crops and alleviate, rather than exacerbate, recent concerns over the food-versus-fuel tradeoff.

Limited research information exists on how optimal management practices and production costs vary between prime and marginal production environments. However, this knowledge is of central importance in addressing under what conditions farmers will opt to produce bioenergy crops. Several studies have addressed optimal nitrogen (N) fertilization management for switchgrass produced as a bioenergy crop, including potential interactions of nitrogen with other fertilizers, soil acidity, water stress, and harvest methods (Muir et al. 2001; Madakadze et al. 1999; Vogel et al. 2002; Stroup et al. 2003; Thomason et al. 2005; Stout, Jung, and Shaffer 1988; Sanderson and Reed 2000; Hopkins and Taliaferro 2004; Reynolds, Walker and Kirchner 2000). Interactions between N and physiogeographic characteristics of the production environment such as drainage (well drained vs. poorly drained), land positioning (flood plain vs. upland) and slope (level versus sloping) are less well understood. Stroup et al. (2003) and Stout, Jung, and Shaffer (1988) address how soil moisture and water availability influence yields, but do not provide a comparison of these findings across varied production environments. Neither does previous research address interactions of nitrogen with seeding rate. The seeding rate decision occurs during establishment in the first year of production. Its impact, however, has potential to influence net revenues beyond the establishment year if yield compensation occurs on plots with a low seeding rate over time, for example through increased tillering or increased above ground biomass per plant, so that no significant yield difference exists between with plots receiving a high seeding rate treatment. The first nitrogen application occurs in the year following establishment and continues annually for the remainder of the stand's lifespan. Potential interactions with seeding rate exist if nitrogen levels affect yield compensation on plots with low seeding rates differently than for plots with high seeding rates.

These potential interactions carry with them considerable economic significance. Differences in land suitability for alternative crops affect rental rates and land opportunity costs. Nitrogen fertilizer and seed costs are currently rising and together represent a considerable portion of total production costs. Many studies exist that determine per-ton production and harvest costs of switchgrass produced as a bioenergy crop (Duffy and Nanhou 2002; Hallam, Anderson, and Buxtom 2001; Haque et al. 2008; Epplin 1996; Perrin et al. 2008; Walsh 1998; Walsh 1994; Thorsell et al. 2004). Only a few provide cost estimates based on actual yield data. Hallam, Anderson, and Buxtom (2001) estimated per ton costs in Iowa for two production environments, one well suited to row crops and the other to pasture. Results indicated a cost per ton of \$48 ton^{-1} for the cropland location and \$38 ton^{-1} for the pasture location. Haque et al. (2008) estimated the per ton production costs for switchgrass in Oklahoma for four N treatment levels in a single production environment, and reported a per ton cost of just under \$40 for the 60 lbs N treatment level. Perrin et al. (2008) calculated farm-scale production costs for ten switchgrass growers in the central plains and obtained estimates ranging from \$46 to \$78 ton^{-1}. None of these studies, however, address how N and seeding rate treatments interact with production environment to influence cost estimates.

The objectives of this research were (a) to compare switchgrass yields as influenced by seeding rate and nitrogen fertilization rates in low-, intermediate-, and high-yielding switchgrass production environments commonly found in western Tennessee, (b) to determine the economically-optimal seeding rate and nitrogen fertilization rate for each environment, and (c) to calculate the per-ton production and harvest costs in each environment for different levels of seeding rate and N treatments. Analysis of the results focused on how optimal input rates and unit production costs varied among production environments and across time. As markets for dedicated energy crops are created and expand, this knowledge will help enhance our understanding of the potential impacts of switchgrass on farm-level cropland allocation and whole-farm net revenues for similar production environments.

DATA AND METHODS

Experiment Design

Switchgrass yield data from 2004 through 2006 were obtained from a field experiment conducted at the University of Tennessee Milan Research and Education Center, Milan, TN. Four locations were chosen to represent the predominant physiogeographic landscape positions and soil types found in West Tennessee. Two well drained landscapes were selected to represent high-yield production environments. They are descriptively defined here as (1) a well to moderately well drained level upland (WDLU), and (2) a well to moderately well drained floodplain (WDFP). WDLU is comprised of Lexington, Loring and Grenada silt loam soils and WDFP contains Vicksburg and Collins silt loam. The third and fourth landscapes were selected to represent poorly drained intermediate and marginal yield environments, respectively. They are defined as (3) a poorly drained, eroded sloping upland (PDSU), and (4) a poorly-drained floodplain (PDFP). PDSU includes Lexington, Loring and Grenada silt loam and PDFP is comprised of Falaya and Waverly silt loams. Both PDSU and PDFP have a root restrictive frangipan, and are characteristic of fields in West Tennessee that qualify for the Conservation Reserve Program (CRP).

The experiment at each location was established in 2004 as a randomized complete block with four repetitions based on seeding rate (SR) treatments of 2.5, 5.0, 7.5, 10.0, and 12.5 lbs acre^{-1} of pure live seed. Main plots were 96 feet long by 15 feet across. All plots were seeded with the Alamo lowland switchgrass variety using a no-till drill the first week in June, 2004. Soil tests conducted at each experiment location indicated medium to high levels of phosphorous and potassium and a soil pH above 5.0 indicating no need for additional fertilizer or lime applications. In 2005, main plots were split in strips based on N rate fertilization treatments (NR) of 0, 60, 120, and 180 lbs acre^{-1}. In each subsequent year of the experiment, sub-plots received an NR treatment identical to the 2005 level. No N was applied in 2004 to mitigate competition with weed populations during establishment. Plots were harvested annually following the first killing frost beginning in 2004, with specific dates ranging from late October to late November.

ANOVA Analysis

Yield data were analyzed for significant differences in SR and NR main effects and their interactions from 2004-2006 using a repeated measures strip-plot ANOVA with random repetitions. SR, NR, and YEAR were considered fixed effects while the repetitions (REP) were considered random effects. In 2004, yield observations were recorded at the SR x REP level. In 2005 and 2006 annual yield observations were recorded at the NR x SR x REP level. Two challenges arose during the model specification. First, switchgrass is a perennial grass and yields recorded in subsequent years from the same sub-plot represent repeated measures on the same subject over time. Given that yield outcomes from adjacent years will be more closely correlated with each other than with outcomes from years that are further apart, we controlled for the possibility of autocorrelation though the specification of a repeated measures ANOVA with an autoregressive covariance structure (Little et al. 2006). Second, the strip-plot experimental design resulted in three plot sizes used to statistically estimate SR and NR main effects and the SR x NR interaction. NR main effect plots measured 24 ft wide by 75 ft long and sub-plots used to measure the SR x NR interaction measured 24 ft long by 15 ft wide. To control for these differences, the ANOVA model was specified to include a separate error term for each.

The mixed model used for this experiment was,

$$Y_{ijkt} = \mu_{ijt} + r_k + a_{ik} + b_{jk} + c_{ijk} + e_{ijkt} \tag{1}$$

where Y_{ijkt} is the observed yield for the k^{th} repeated sub-plot assigned to the ij^{th} SR x NR treatment combination in year t, μ_{ijt} is the mean of the ij^{th} SR x NR treatment combination across all repetitions in year t, r_k is a random error term representing repetition effects, and terms a_i, b_j, and c_{ij} represent error terms for the i^{th} SR main effect, the j^{th} NR main effect, and the ij^{th} SR x NR interaction effect, respectively. The last term e_{ijkt} represents the $ijkt^{th}$ sub-plot error. All error terms are assumed identically and individually distributed.

The term μ_{ijt} expressed in terms of main effects and interaction effects is,

$$\mu_{ijt} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_t + (\gamma\alpha)_{ti} + (\gamma\beta)_{tj} + (\gamma\alpha\beta)_{tij} \tag{2}$$

where μ is the overall mean, α_i is the i^{th} SR main effect, β_j is the j^{th} NR main effect, γ_t is the t^{th} main YEAR effect, and the remaining terms in Equation (2) represent the complete set of interaction effects among SR, NR, and YEAR.

The MIXED procedure in SAS release 9.1 (SAS Institute) was used to estimate the repeated measures ANVOA with a strip-plot experimental design as specified in equation (1) (Schabenberger 2008; Littell et al. 2006). The RANDOM statement included the terms *rep*, *sr*rep*, *nr*rep*, and *sr*nr*rep* to control for the random and strip-plot error terms (Schabenberger 2008). The REPEATED statement was used to control for autocorrelation of yield observations across time. Among alternative covariance structures proposed by Littell et al. (2006) for repeated measures analysis, the first-order autoregressive AR(1) structure was selected based on -2 Res Log Likelihood and -2 REML Log Likelihood fit statistics. Mean comparison tests between treatment levels were conducted to explore significant differences among least square means (Littell et al. 2006; Saxton1998).

Switchgrass Prices

Markets for switchgrass produced as a bioenergy crop do not exist (Epplin et al. 2007). As a result, no reliable prices are available to use in calculating optimal input rates or potential net revenues. While switchgrass has historically been planted as a forage crop and related markets may exist, its production as cellulosic feedstock differs in that the goal is to maximize biomass yield per acre rather than forage quality. One alternative to using current market prices is to use the breakeven price that is expected to make switchgrass competitive with corn as an ethanol feedstock. Many such estimates exist. As a benchmark, this analysis uses a farm gate price of $40/dry ton as identified in previous research on the economic impact of bioenergy crops on U.S. agriculture (De La Torre Ugarte et al. 2003).

Economically Optimal Input Rates

This section presents the procedure used to determine economically optimal SR and NR levels for the production of switchgrass as a bioenergy crop. Initial ANOVA results and estimation of two-input production functions showed no significant interactions between SR and NR. In addition, the production function estimates provided a poor statistical fit most likely due to differences in the timing and frequency of the SR and NR input decisions. Based on these initial observations, the methods used to determine the economically optimal SR and NR levels were determined independently of one another.

Seeding Rate

The economically optimal seeding rate occurs where the value of additional yield generated by a marginal increase in seed density just pays for the additional seed cost. Since the influence of seeding rate on yield potentially carries beyond the establishment year, the calculation of net revenues must allow for this possibility:

$$NR_i^{SC} = \sum_{t=0}^{n} \frac{P \times Y_{it}(SR)}{(1+r)^t} - w \times SR\,, \tag{3}$$

where NR^{SC} for each production environment *i* was defined as the net return to seed costs (\$/acre), *P* was the switchgrass price (\$/ton), Y_t was the switchgrass yield in year *t* as a function of seed density, *w* was the price of seed (\$/lb), *SR* was the seeding rate (lbs/acre), and the term $(1 + r)^t$ was used to discount annual revenues into constant 2004 base year dollars for each of *n* time periods.

The functional relationship between yield and seed density for switchgrass as a bioenergy crop is unknown. Two common hypotheses regarding the yield-density relationship are (1) that E[Y] is an increasing function of SR that becomes asymptotic above some critical density level

SR*, and (2) that E[Y] is a parabolic function that achieves a maximum yield at a density level SR^{max} (Schabenberger and Pierce, 2002). To explore these ideas empirically, a Bleasdale-Nelder yield-density model was estimated for each production environment using the 2004-2006 data for each production environment (Schabenberger and Pierce, 2002):

$$\ln\{ W_i \} = \frac{-1}{\theta_i} \ln\{ (\alpha + \beta_i SR) \} + e_i \tag{4}$$

where W_i denotes the cumulative switchgrass yield per pound of live seed (tons/lb) from production environment *i*, *SR* denotes seeding rate (lbs/acre), and α, β, and θ are parameters to be estimated (Schabenberger and Pierce, 2002). Using this function, yield per acre can easily be obtained by from $Y = SR \times W$. The asymptotic yield-density relationship is obtained when θ = 1. In this case, the asymptotic per-acre yield is given by the term 1/β. Alternatively, the parabolic relationship is obtained whenever $\theta < 1$. In this case, the seed density at which per-acre yield is maximized occurs at,

$$SR^{\max} = \frac{\alpha}{\beta}\left(\frac{\theta}{1-\theta}\right). \tag{5}$$

The NLIN procedure in the SAS 9.1 statistical package (SAS Institute, 2002) was used to estimate the yield-density response function as stated in equation (4) (Schabenberger and Pierce, 2002). Nitrogen levels in each of the four experiment locations were fixed at 60 lbs. The following hypotheses were tested using F-tests on linear restrictions:

(1) $H1_o$: $\theta_1 = \theta_2 = \theta_3 = \theta_4 = 1$, i.e. yield-density relationships are asymptotic for all production environments; $H1_a$: at least one $\theta_i \neq 1$, i.e., at least one production environment is not asymptotic; and (2) $H2_o$: $\beta_1 = \beta_2 = \beta_3 = \beta_4$, i.e. production environments do not differ in parameter β; Ha: $\beta_i \neq 1$, i.e., at least one production environment differs in the parameter β.

Nitrogen Fertilization Rates

A quadratic yield response function for N was estimated for 2005 and 2006 using data from each production environment:

$$\begin{aligned} Y = {} & \alpha_1 + \alpha_2 WDLU + \alpha_3 PDFP + \alpha_4 PDSU + \beta_1 NR + \beta_2 NR^2 \\ & + \beta_3 (NR \times WDLU) + \beta_4 (NR^2 \times WDLU) + \beta_5 (NR \times PDFP) \\ & + \beta_6 (NR^2 \times PDFP) + \beta_7 (NR \times PDSU) + \beta_8 (NR^2 \times PDSU) + u \end{aligned} \tag{9}$$

where *Y* was the switchgrass yield (tons acre^{-1}), *NR* was the applied N rate (lbs acre^{-1}); *WDLU* was a dummy variable equal to 1 for the well drained level upland environment and 0 otherwise; *PDFP* was a dummy variable equal to 1 for the poorly drained flood plain environment and 0 otherwise; *PDSU* was a dummy variable equal to 1 for the poorly drained sloping upland environment and 0 otherwise; NR x $WDLU$, NR^2 x $WDLU$, NR x $PDFP$, NR^2 x $PDFP$, NR x $PDSU$, and N^2 x $PDSU$ were interactions between NR and production environment dummy variables; and *u* was a random error. The well drained flood plain (WDFP) environment was not included in the model, and serves as thus serves as the base environment from which to interpret the model. The quadratic term NR^2 was included to account for the diminishing marginal productivity of N observed in Table 2.

The response function was estimated with SAS 9.1 (SAS Institute, 2002). The following hypotheses were tested using F-tests on linear restrictions: (1) $H1_o$: $\alpha_2 = \alpha_3 = \alpha_4 = 0$ i.e. all production environments share an identical intercept; $H1_a$: at least one of α_2, α_2, or $\alpha_3 \neq 0$, i.e., the intercept differs for at least one production environment; and (2) $H2_o$: $\beta_3 = \beta_4 = \ldots = \beta_8 = 0$, i.e. the slope of NR is identical for all production environments; $H2_a$: at least one of β_3, β_4, . . . , $\beta_8 \neq 0$, i.e., the slope of NR differs for at least one production environment.

Production Costs

Production costs were estimated for each environment in each year of the experiment and for each SR and NR treatment combination using enterprise budgets developed by the authors for the establishment, annual maintenance, and annual harvesting of no-till switchgrass produced as a bioenergy crop. The machinery and labor schedule used in constructing each of these budgets is included in Table 3. Prices and machinery cost parameters were obtained from the University of Tennessee Extension 2007 Switchgrass Production Budget (Gerloff, 2007) and are summarized in Table 4.

The establishment budget included all production operations conducted prior to harvest during 2004 and includes seed, herbicide and fungicide costs in addition to all related machinery and labor costs (Table 5). Seed costs and operating capital were the only establishment costs assumed to vary across production environments. Soil tests from the experimental plots did not indicate a need for phosphorous or potassium fertilizers or lime and no costs were included. Likewise none of the experimental plots were re-seeded and no re-seeding costs were included in these estimates.

The maintenance budget included annual costs for herbicide, fungicide and N fertilizer costs, as well as machinery and labor costs needed for their application (Table 6). Fertilizer costs and operating capital were the only costs assumed to vary across NR treatments for the 60, 120, and 180 lbs acre^{-1} levels. Machinery costs are also expected to vary at the 0 lbs acre^{-1} since fewer field operations are required.

The harvest budget included all machinery and labor costs for mowing, raking, bailing, and bale staging (Table 7). The mowing and raking operations were assumed to remain constant on a per-acre basis for all yield levels. Time requirements for the bailing and staging field operations were assumed to operate as a function of yield. Baling was assumed to operate at a rate of 5 tons hour^{-1} and the staging operating was expected to operate at a rate of 8 bales hour^{-1} (or, equivalently, 6 tons hour^{-1}) for large round 1500 lb bales (Table 4). As a result, harvest costs vary by year and by SR and NR treatment levels. Additional harvest costs that vary with yield include twine and operating capital. Post-harvest storage, loading and transportation costs of the bales were not included in this analysis.

The production of perennial energy crops such as switchgrass results in a flow of annual production costs and revenues across the stand's estimated lifespan. To permit a fair comparison across treatment levels, the time preference of money requires that these flows be valued at the same point in time (AAEA 2000). Both 5- and 10-year expected lifespans were considered. The 5-year lifespan was chosen since it likely reflects the economic lifespan of a switchgrass stand under contract with a biorefinery or other buyer. The 10-year lifespan was chosen as it reflects the productive lifespan of the stand from an agronomic perspective.

The cost estimation procedure was completed in three steps. First, all maintenance, land, and harvesting costs incurred over the estimated lifespan of the switchgrass stand were discounted to their establishment year dollar value (2004) using a standard net present value (NPV) formula (Table 8). Land costs were set at $100 per acre for all four production environments (Goddard 2008). The sensitivity of Second, annualized production costs were calculated by summing establishment year costs with the present values of maintenance and harvest costs, and then amortizing this value across the stand's lifespan. Finally, per-ton production costs for each treatment combination were obtained by dividing annual costs by average yield (Table 8).

RESULTS

Biomass Yields

As expected, NR, YEAR, and the NR x YEAR interaction were significant across all production environments in the ANOVA analysis (Table 9). The SR main effect was statistically significant for the WDFP and PDFP environments, and the SR x YEAR interaction term was significant in the WDLU and PDFP environments. YEAR was by far the most dominant effect. The SR x NR and YEAR x SR x NR interaction terms were not significant in any production environment, which suggests that the yield response of switchgrass to SR operates independently of NR and vice versa.

To explore these differences in greater detail, paired difference tests were conducted for the SR x YEAR and NR x YEAR levels of interaction. Surprisingly, only a few significant differences in average yields were observable between SR treatment levels for the period 2004-2006 (Figure 1). In 2004, the only difference occurred in the WDLU environment between the 2.5 and 12.5 lbs acre^{-1} SR treatment levels. In 2005, no significant differences in average yields were observed for any SR treatment level, suggesting that yield compensation did occur on plots with lower seeding rates. In 2006, significant differences in yields were indicated for the WDFP environment at the 7.5, 10.0 and 12.5 lbs acre^{-1} SR treatment levels. For the PDFP environment a significant increase in average yields occurred between the 2.5 and 5.0 lbs acre^{-1} SR levels. For the WDLU environment, the highest SR treatment had a significantly lower yield than did lower levels. Likewise for the PDSU environment, average yields were significantly lower for the 5 lb acre^{-1} than for the 2.5 lbs acre^{-1} SR treatment level. Cumulative yields over the period 2004-2006 were also calculated to explore whether there was difference across SR treatment levels over time (Figure 2). In each of the production environments except PSDU, an increase in cumulative yield is observable when viewing SR treatments with the same landscape, but no formal statistical tests were carried out to check their significance.

Differences in average yields based on NR treatment levels were more prominent. In 2005, significant differences were found within all production environments except WDLU (Figure 3). For the WDFP and PDSU environments, average yields were significantly higher at 60 lbs acre^{-1} than for 0 lbs acre^{-1}. For the PDFP environment, NR treatment levels increased average yields up until the 120 lbs acre^{-1} treatment level. The WDLU environment provided the highest overall average yields but showed no response to NR at any level. For 2006, these NR treatment effects became more prominent. For the WDFP and PDSU environments, the differences in average yields between 0 and 60 lbs acre^{-1} were more pronounced than in 2005, and both showed a significant decrease in average yield at the 180 lbs acre^{-1} NR level, suggesting a possible quadratic relationship between yield and NR. Interestingly, average yields for the most productive environment, WDLU, increased significantly between 0 and 60 lbs acre^{-1}, whereas for the least productive environment, PDFP, average yields increased significantly across all four NR levels.

Economically Optimal Input Rates

The estimated Bleasdale-Nelder yield-density function for switchgrass production in West Tennessee over the period 2004-2006 is presented in Table 10. Evaluation of the F statistic (F = 84.08, $p = 0.00$) for the full model, where the parameters β_i and θ_i were estimated separately for each production environment, suggests that seeding rate significantly explained cumulative yield response. The model restricted under $H1_o$: $\theta_1 = \theta_2 = \theta_3 = \theta_4 = 1$ was rejected ($F = 282.29$) at a 5% significance level, implying that parameter values for θ_i differ across production environments and that at least one landscape exhibits a parabolic yield-density relationship (i.e. $\theta_i < 1$).

Likewise, the model restricted under $H2_o$: $\beta_1 = \beta_2 = \beta_3 = \beta_4$ was also rejected (F = 30.94) at the 5% significance level, implying that at least one parameter value for β_i also differs across production environments. Consequently, we use the full model as specified in equation (4) in exploring optimal seeding rates.

The relationship between yield, seeding rate, and net returns to seed costs for the poorly drained sloping upland (PDSU) is illustrated in Figure 3. A maximum cumulative yield of 14.2 tons acre^{-1} was achieved at a seeding rate of 5.7 lbs acre^{-1} with an associated per-acre net return to seed costs of \$478. Reducing the seeding rate from 5.7 to 3.8 lbs acre^{-1} results in a decreased cumulative yield to 13.9 tons acre^{-1} but increases the net return to seed costs to \$478 acre^{-1}, \$23 acre^{-1} higher than with the yield maximizing seeding rate. A set of complete results for both the yield maximizing and economically optimal seeding rates is provided in the final column of Table 10. Optimal seeding rates are highest for the two well drained landscapes, WDLU and WDPF, at 4.5 and 4.4 lbs acre^{-1}, respectively (Figure 5). The two poorly drained landscapes, PDSU and PDFP, have economically optimal seeding rates that are almost one pound per acre less at 3.8 and 3.2 lbs acre^{-1}, respectively.

The estimated switchgrass yield response function to nitrogen for 2006 also showed a high level of overall significance (F = 47.86) and a good statistical fit (Adj. R^2 = 0.6177) (Table 11). The coefficients on N and N^2, representing the WDFP environment, had the expected signs and were both significantly different from zero. Production environment interaction terms with N and N^2 were also all significantly different from the base WDFP environment, with the exception of the quadratic interaction term for the PDSU environment. When adjusted for their differential slopes, coefficients on the quadratic term for both the WDLU and PDFP environments become positive, but only slightly greater than zero, suggesting that yield may respond linearly to N over the 0 to 180 lbs acre^{-1} data range in these environments. The three dummy variables WDLU, PDFP, and PDSU representing differential intercept shifters for their respective production environments were also all significantly different from the WDLU base environment. In 2006, the economically optimal N rates were 83 lbs acre^{-1} for the WDFP environment, 89 lbs acre^{-1} for the WDLU environment for a switchgrass price of \$40 dry ton^{-1} and an N price of \$0.42 lb^{-1} of applied N. For the poorly drained landscapes, the economically optimal rates were much higher given the larger differential slope coefficients on the N x PDFP and N x PDSU interaction terms and occurred outside of the range of data. In both cases, the estimated optimal N rate was above 180 lbs acre^{-1}. The authors do not recommend using these outside of the context of this dataset.

Production Costs

Production costs per ton of switchgrass as a bioenergy crop are included in Table 12 for two scenarios. The "typical" recommendations represent seeding rates and nitrogen fertilization rates similar to current extension recommendations. The low cost treatment combinations represent the combination of SR and NR that provided the lowest per-ton production costs in each production environment. The cost of production for an expected ten-year lifespan for the "typical" recommendation ranged from \$45 dry ton^{-1} in a well drained level upland (WDLU) environment ideal for the production of row crops to \$70 dry ton^{-1} in a marginal, poorly drained flood plain environment (PDFP) in which the switchgrass stand was slow to establish and which demonstrated lower overall yields. Per-ton costs for the other two environments were \$47 dry ton^{-1} in a well drained flood plain (WDFP) environment and \$48 dry ton^{-1} for a poorly drained sloping upland (PDSU) environment. Approximately 50% of the final cost estimate was attributable to harvesting and staging costs, 30% to land costs, and the remaining 20% to establishment and maintenance costs. Cost estimates from the 5-year expected lifespan have a similar cost composition but are approximately $5-$8 higher. The decrease in the cost per ton over a 10-year period can be viewed in Figure 6.

In three of four production environments, the low-cost SR and NR treatment combination differed from the "typical" 5 lbs acre^{-1} SR and 60 lbs acre^{-1} NR treatment combination. The two poorly drained locations, PDFP and PDSU, had low cost treatment combinations with NR levels of 180 and 120, respectively. The two upland environments, WDLU and PDSU, both had low-cost treatment combinations with a seeding rate of 2.5 lbs acre^{-1}. Per ton costs estimated using these treatment combinations decreased most dramatically for the poorly drained locations, with per-ton cost estimates decreasing by $7 and $5 dry ton^{-1} for the PDFP and PDSU locations, respectively. In the WDLU environment, costs decreased by $3 dry ton^{-1}. Figure 7 provides a means of comparing results from the low cost treatments scenario with the typical recommendations (Figure 6) over time.

Discussion

The final per-ton cost estimates compare favorably with the most recent similar studies (Duffy and Nanhou 2002; Hallam, Anderson, and Buxtom 2001; Haque et al. 2008; Perrin et al. 2008). However, at a current projected price of $40 dry ton^{-1} (De La Torre Ugarte et al, 2003), the net returns to a switchgrass cropping enterprise would be negative. Many questions remain with respect to farm-level production, management, and logistics of switchgrass as a bioenergy crop. First, this study did not consider on-farm storage or transportation costs to a biorefinery. Given the large volume of biomass that will be required by bio-refineries on a consistent year-round basis, farmers are expected to play a predominant role in providing such services (Epplin et al. 2007). These costs can be significant and must be considered when determining the cost per ton of switchgrass delievered to a biorefinery (Cundiff and Marsh 1996; Epplin 1996; Petrolia 2006;

Walsh 1998). Future research in this area could investigate economically optimal on-farm storage practices to minimize dry matter loss.

Second, this paper ignores risks associated with producing switchgrass as a bioenergy crop. One production risk not addressed here is stand failure. Future research could address how seeding rate interacts with other factors that influence the probability of reseeding, such as planting equipment, planting depth, soil moisture and weather conditions and what those costs are. Market risks, such as the potential for fluctuations in net revenues of current farm enterprises relative to switchgrass and the emergence of new and more profitable enterprises are also important. Given the high initial investment and multi-year production process, future research could address how these factors influence a farmer's willingness to adopt a bioenergy crop.

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Table 1. Average Switchgrass Yields by Seeding Rate Treatment and Production Environment, Milan, TN, 2004-2006 (dry tons/acre)

Production Environment	Year	Seed Density (lbs/acre)				
		2.5	5	7.5	10	12.5
Well Drained Flood Plain (WDFP)	2004	0.73	0.75	1.08	1.39	1.38
	2005	4.39	5.11	4.64	5.37	5.33
	2006	6.80	6.52	6.03	7.46	8.01
	5-Year Projected Avg. a/	5.10	5.08	4.69	5.70	6.02
	10-Year Projected Avg b/	5.95	5.80	5.36	6.58	7.01
Well Drained Level Upland (WDLU)	2004	0.92	1.07	1.29	1.49	1.85
	2005	5.18	5.09	5.23	5.35	5.16
	2006	10.28	10.16	10.69	10.46	9.44
	5-Year Projected Avg.	7.38	7.30	7.64	7.53	6.88
	10-Year Projected Avg.	8.83	8.73	9.16	9.00	8.16
Poorly Drained Flood Plain (PDFP)	2004	0.50	0.84	0.81	1.03	0.38
	2005	2.78	3.43	2.98	2.94	2.93
	2006	3.52	4.93	4.93	5.22	4.97
	5-Year Projected Avg.	2.77	3.75	3.65	3.82	3.67
	10-Year Projected Avg.	3.15	4.34	4.29	4.52	4.32
Poorly Drained Sloping Upland (PDSU)	2004	0.93	1.08	1.01	1.04	0.92
	2005	4.06	3.84	4.04	3.97	3.92
	2006	8.60	7.25	7.98	8.06	8.22
	5-Year Projected Avg.	6.16	5.30	5.78	5.82	5.90
	10-Year Projected Avg.	7.38	6.28	6.88	6.94	7.06

a/ 2007-2009 yields assumed equal to the 2006 yield.
b/ 2007-2013 yields assumed equal to the 2006 yield.

Table 2. Average Switchgrass Yields by Nitrogen Rate Treatment and Production Environment, Milan, TN, 2004-2006 (dry tons/acre)

Production Environment	Year	Nitrogen Rate (lbs/acre)			
		0	60	120	180
Well Drained Flood Plain (WDFP)	2004 a/	1.06	1.06	1.06	1.06
	2005	4.09	5.48	5.16	5.16
	2006	5.15	8.14	7.99	6.57
	5-Year Projected Avg. b/	4.05	6.12	5.97	5.12
	10-Year Projected Avg c/	4.60	7.13	6.98	5.85
Well Drained Level Upland (WDLU)	2004	1.32	1.32	1.32	1.32
	2005	5.22	5.06	5.17	5.36
	2006	8.64	10.42	10.68	11.09
	5-Year Projected Avg.	6.41	7.44	7.63	7.91
	10-Year Projected Avg.	7.52	8.93	9.15	9.50
Poorly Drained Flood Plain (PDFP)	2004	0.71	0.71	0.71	0.71
	2005	1.69	2.67	3.57	4.12
	2006	3.19	4.04	4.96	6.67
	5-Year Projected Avg.	2.35	3.06	3.79	4.92
	10-Year Projected Avg.	2.77	3.55	4.38	5.80
Poorly Drained Sloping Upland (PDSU)	2004	0.99	0.99	0.99	0.99
	2005	3.20	4.09	4.42	4.17
	2006	4.22	8.46	10.33	9.08
	5-Year Projected Avg.	3.35	6.08	7.27	6.47
	10-Year Projected Avg.	3.78	7.27	8.80	7.78

a/ Nitrogen treatments began in 2005, the 2004 yields represent average yields for each production environment during establishment.
b/ 2007-2009 yields assumed equal to the 2006 yield.
c/ 2007-2013 yields assumed equal to the 2006 yield.

Table 3. Machinery and Labor Schedule for No-Till Switchgrass Production in West Tennessee

Month	Operation	Equipment	Hours per Acre	
			Machine	Labor
Establishment Operations				
August	Pre-Emergence Burndown (x 2)	Sprayer, 60' boom; Tractor, 150hp	0.03	0.03
September	Pre-Emergence Burndown	Sprayer, 60' boom; Tractor, 150hp	0.03	0.03
May	Plant	No-Till Drill, 16 row; Tractor, 150hp	0.24	0.29
	Pre-Emergence Burndown (x 2)	Sprayer, 60' boom; Tractor, 150hp	0.06	0.06
	Spread Fertilizer	Tractor, 150 HP	0.07	0.08
	Post-Emergence Spray (x 3)	Sprayer, 60' boom; Tractor, 150hp	0.08	0.10
Annual Maintenance Operations				
May	Herbicide Spray	Sprayer, 60' boom; Tractor, 150hp	0.03	0.03
	Spread Fertilizer	Tractor, 150hp	0.07	0.08
Annual Harvest Operations				
Nov/Dec	Mow	Mower; Tractor, 150hp	0.44	0.55
	Rake	Rake; Tractor, 150hp	0.29	0.36
	Bale	Round Baler, 1500 lbs/bale; Tractor, 150hp	Varies a/	Varies
	Stage/Load	Front End Loader; Tractor, 150hp	Varies	Varies

a/ Varies as a function of yield.

Table 4. Machinery Equipment Costs for No-Till Switchgrass in West Tennessee

		------------------------ Equipment ------------------------						
Item	**Unit**	**No-till Drill, 16 Row 7.5"**	**Sprayer, 60' Boom**	**Mower**	**Rake**	**Round Baler, 1500 lbs/bale**	**Front End Loader**	**Tractor, 150HP**
Cost Calculation Parameters a/								
Purchase Price (PP)	$	$17,000	$8,400	$6,500	$3,000	$23,000	$7,500	$97,250
Useful Life	Hours	1500	1500	2000	2500	1500	1000	12000
Annual Use	Hours	100	100	133	120	210	100	666
Repair Cost	% of PP	75	70	150	60	90	40	100
Salvage Value	% of PP	10	10	10	10	10	10	10
Field Speed	miles/hour	5.0	6.5	5.0	6.0	---	---	---
Implement Width	Feet	10	60	7	9	---	---	---
Field Efficiency	%	0.7	0.65	0.8	0.8	---	---	---
Field Performance	hours/dry ton	---	---	---	---	0.200 b/	0.167 c/	---
Field Performance	hours/acre	0.236	0.033	0.295	0.191	varies	varies	varies
Labor	hours/acre	0.295	0.041	0.368	0.239	varies	varies	varies
Fuel Use	gallons/hour	---	---	---	---	---	---	6.6
Ownership Costs								
Taxes, Insurance, and Housing d/	$/hour	$5.10	$2.52	$1.47	$0.75	$3.29	$2.25	$4.38
Depreciation and Interest e/	$/hour	$13.60	$6.72	$3.91	$2.00	$8.76	$6.00	$11.68
Operating Costs								
Repairs and Maintenance	$/hour	$8.50	$3.92	$4.88	$0.72	$13.80	$3.00	$8.10
Labor Cost	$/hour	$8.50	$8.50	$8.50	$8.50	$8.50	$8.50	$8.50
Fuel Cost f/	$/hour	---	---	---	---	---	---	$13.80

a/ Cost calculation parameters are taken from the 2008 University of Tennessee-Extension Switchgrass Production Budget.
b/ Assumes the baler operates at 5 ton/acre.
c/ Assumes the staging and loading process operates at 8 bales/hour (i.e. 6 tons/hour for 1500 lb bales).
d/ Annual TIH assumed to be 3% (ASAE, 2006).
e/ Using the capital recovery method, 8% interest rate (AAEA, 2000).
f/ Fuel price = $2.10 USD.

Table 5. Establishment Budget for No-Till Switchgrass in West Tennessee

	Unit	Quantity	Unit Price	Establishment Costs by Seeding Rate				
				2.5 lbs	5.0 lbs	7.5 lbs	10.0 lbs	12.5 lbs
Variable Expenses								
Seed	Lbs/Ac PLS	*Varies*	$20.00	$50.00	$100.00	$150.00	$200.00	$250.00
Herbicide								
Roundup Original Mix	Pt/Ac	3.2	$2.24	--------------------------$7.17--------------------------				
Cimarron	Oz/Ac	0.1	$19.00	--------------------------$1.90--------------------------				
Grass herbicide	App/Ac	3	$7.00	-------------------------$21.00-------------------------				
Operating Capital (6 months)	%	*Varies*	8.0	$3.83	$5.83	$7.83	$9.83	$11.83
Machinery Expenses								
Diesel Fuel	Gal/Ac	4.17	$2.10	--------------------------$8.76--------------------------				
Repair and Maintenance	Acre	1	$6.80	--------------------------$6.80--------------------------				
Depreciation	Acre	1	$7.92	--------------------------$7.92--------------------------				
Interest	Acre	1	$5.17	--------------------------$5.17--------------------------				
Labor Expenses								
Operator Labor	Hrs/Ac	0.62	$8.50	--------------------------$5.27--------------------------				
Total Establishment Cost	**$/Ac**			**$117.81**	**$169.81**	**$221.81**	**$273.81**	**$325.81**

Table 6. Annual Maintenance Budget for No-Till Switchgrass in West Tennessee

	Unit	Unit Price	Quantity	Production Costs by Nitrogen Rate			
				NR=0	NR=60	NR=120	NR=180
Variable Expenses							
Fertilizer							
Nitrogen	Lbs/Acre	$0.42	*Varies*	$0.00	$25.20	$50.40	$75.60
Herbicide							
Cimarron	Oz/Acre	$19.00	0.1	----------------------$1.90----------------------			
Grass herbicide	Aplic/Acre	$7.00	1	----------------------$7.00----------------------			
Operating Capital (6 months)	%	8.0		$0.39	$1.46	$2.47	$3.48
Machinery Expenses							
Diesel Fuel	Gal/Acre	$2.10	*Varies*	$0.49	$1.67	$1.67	$1.67
Repair and Maintenance	Acre	*Varies*	1	$0.34	$0.88	$0.88	$0.88
Depreciation	Acre	*Varies*	1	$0.39	$0.94	$0.94	$0.94
Interest	Acre	*Varies*	1	$0.26	$0.65	$0.65	$0.65
Labor Expenses							
Operator Labor	Hr/Acre	$8.50	3.93	$0.68	$0.93	$0.93	$0.93
Total Annual Maintenance Cost	**$/Ac**			**$11.45**	**$40.63**	**$66.84**	**$93.05**

Table 7. Annual Harvest Budget for No-Till Switchgrass for a Poorly Drained Sloping Upland (PDSU) Environment in West Tennessee (Nitrogen rate = 60 lbs/acre; Seed Density = 5 lbs/acre)

	Unit	Units/Acre	Unit Cost	2004	2005	2006
Variable Expenses						
Triple Tie Twine	Twine/Bale	*Varies*	$1.19	$1.71	$6.62	$14.01
Operating Capital (6 months @ 8%)	Acre	1	*Varies*	$1.01	$2.53	$4.81
Machinery Expenses						
Diesel Fuel	Gallon	*Varies*	$2.10	$11.85	$26.81	$49.30
Repair and Maintenance	Acre	1	*Varies*	$11.72	$29.79	$56.92
Depreciation and Interest	Acre	1	*Varies*	$14.30	$34.94	$65.94
Taxes, Insurance and Housing	Acre	1	*Varies*	$5.36	$13.11	$24.74
Labor Expenses						
Operator Labor	Hour	*Varies*	$8.50	$18.18	$41.12	$75.57
Total Annual Harvest Cost b/	Acre	1	*Varies*	$45.97	$113.81	$215.70

a/ The full set of harvest cost results are presented in Appendix Table 2.
b/ Yields in 2004, 2005, and 2006 were 1.08, 4.18, and 8.83 dry tons/acre, respectively.

Table 8. Example Calculation of Annualized Production and Harvest Costs for No-Till Switchgrass Production with a 5-Year Expected Stand Lifespan in a Well Drained Sloping Upland (WDSU) Enivironment, West Tennessee (NR = 60 Lbs/Acre; SR = 7.5 Lbs/Acre)

	Year (time period)					5-Year Expected Stand Lifespan (2004 USD)			
	2004	2005	2006	2007	2008	NPV of Total Production Cost (2004 USD) a/		Annualized Total Production Cost (2004 USD)	
Item	**(t =1)**	**(t = 2)**	**(t =3)**	**(t =4)**	**(t = 5)**	**$/Acre**	**%**	**$/Year**	**$/Ton**
Yield (dry tons/acre)	1.08	4.18	8.83	8.83	8.83				
Establishment Cost	$222	$0	$0	$0	$0	**$222**	**15%**	**$51**	**$8.11**
Maintenance Costs	$0	$40	$40	$40	$40	**$132**	**9%**	**$31**	**$4.82**
Harvest Costs	$46	$114	$216	$216	$216	**$666**	**46%**	**$154**	**$24.32**
Land Costs	$100	$100	$100	$100	$100	**$431**	**30%**	**$100**	**$15.74**
Total Production Costs	$368	$254	$356	$356	$356	**$1,452**	**100%**	**$337**	**$53.03**

a/ Discount rate = 8%.

Table 9. ANOVA Results for SR, NR, and YEAR Main Effects and their Interactions on Switchgrass Yield, Milan, TN 2004-2006

	WDFP		WDLU		PDFP		PDSU	
Effect	F	*p*-value	F	*p*-value	F	*p*-value	F	*p*-value
SR	2.94	0.066	0.76	0.5678	4.95	0.0136	0.46	0.7645
NR	4.53	0.034	4.51	0.0267	34.7	<.0001	38.18	<.0001
SR x NR	1.05	0.423	1.31	0.2438	0.59	0.8377	0.7	0.7448
YEAR	327.1	<.0001	1431.66	<.0001	371.53	<.0001	659.38	<.0001
YEAR x SR	0.92	0.506	2.08	0.0435	2.29	0.0253	0.91	0.5076
YEAR x NR	4.72	0.000	6.98	<.0001	13.92	<.0001	26.5	<.0001
YEAR x SR x NR	0.82	0.708	0.74	0.8055	0.31	0.9991	0.82	0.7084

Table 10. Switchgrass Seed Density Response Functions by Production Environment

Production Environment	Estimated Bleasdale-Nelder Response Functions	Comparison of Yield (Y^{max}) versus Economic (Y*) Decision Criteria
WDFP	$\hat{Y} = SR \times \left\{ 0.1684 + (0.0578 \times SR)^{\frac{-1}{0.7209}} \right\}$	Y^{max} = 15.3 t/ac Seed Density = 7.4 lbs/ac Net Return = 468 $/acre
	se(α) = 0.2241; se(β) = 0.0127; se(θ) = 0.3440	Y* = 14.8 t/ac Seed Density = 4.4 lbs/ac Net Return = 500 $/acre
WDLU	$\hat{Y} = SR \times \left\{ 0.1684 + (0.0530 \times SR)^{\frac{-1}{0.6753}} \right\}$	Y^{max} = 17.7 t/ac Seed Density = 6.5 lbs/ac Net Return = 576 $/acre
	se(α) = 0.2241; se(β) = 0.0127 ; se(θ) = 0.3440	Y* = 17.2 t/ac Seed Density = 4.5 lbs/ac Net Return = 600 $/acre
PDFP	$\hat{Y} = SR \times \left\{ 0.1684 + (0.1095 \times SR)^{\frac{-1}{0.8982}} \right\}$	Y^{max} = 7.7 t/ac Seed Density = 8.7 lbs/ac Net Return = $381 /ac
	se(α) = 0.2241; se(β) = 0.0127 ; se(θ) = 0.3440	Y* = 6.7 t/ac Seed Density = 3.2 lbs/ac Net Return = 455 $/ac
PDSU	$\hat{Y} = SR \times \left\{ 0.1684 + (0.0643 \times SR)^{\frac{-1}{0.6909}} \right\}$	Y^{max} = 14.2 t/ac Seed Density = 5.7 lbs/ac Net Return = 455 $/ac
	se(α) = 0.2241; se(β) = 0.0127 ; se(θ) = 0.3440	Y* = 13.9 t/ac Seed Density = 3.8 lbs/ac Net Return = 478 $/ac

Notes: Nitrogen rate is fixed at 60 lbs/acre; se = standard errors of estimated parameters; WDFP = well drained flood plain, WDLU = well drained level upland, PDFP= poorly drained flood plain, PDSU=poorly drained sloping upland.

Table 11. Estimated Switchgrass Yield Response Function to Nitrogen

Variable	Year
	2006
Intercept	5.23
	(12.37)***
WDLU	3.47
	(5.81)***
PDFP	-2.01
	(-3.36)***
PDSU	-1.06
	(-1.77)*
N	0.062
	(5.47)***
N2	-0.00031
	(-5.07)***
N x WDLU	-0.032
	(-2.01)**
N2 x WDLU	0.0002
	(2.47)**
N x PDFP	-0.054
	(-3.36)***
N2 x PDFP	0.00037
	(4.29)***
N x PDSU	0.034
	(2.12)**
N2 x PDSU	0.000075
	(-0.88)
Adj. R^2	0.6177
F statistic	47.86***
Observations	320

* Significant at the 0.10 probability level.

** Significant at the 0.05 probability level.

*** Significant at the 0.01 probability level.

Notes: Switchgrass yield (dry tons/acre) was the dependent variable; N was applied nitrogen (lbs/acre); numbers in parentheses are *t* statistics.

Table 12. Projected Per-Ton Costs for Switchgrass Grown as a Bioenergy Crop ($2004)

Production Environment	SR	NR	Cost per Ton a/	Establish-ment Costs	Maint-enance Costs	Harvet Costs	Land Costs
	lbs/acre	lbs/acre	$/ton	%	%	%	%
5-Year Cost Estimates							
"Typical" Recommendation							
WDFP	5	60	$52.41	12%	9%	50%	29%
WDLU	5	60	$51.73	12%	9%	50%	29%
PDFP	5	60	$80.14	15%	11%	37%	37%
PDSU	5	60	$55.26	12%	9%	48%	31%
Low-Cost Treatment Combination							
WDFP	5	60	$52.41	12%	9%	50%	29%
WDLU	2.5	60	$47.73	8%	9%	53%	29%
PDFP	5	180	$70.99	12%	21%	38%	29%
PDSU	2.5	120	$48.00	7%	14%	53%	27%
10-Year Cost Estimates							
"Typical" Recommendation							
WDFP	5	60	$46.75	7%	10%	55%	29%
WDLU	5	60	$45.13	7%	10%	56%	28%
PDFP	5	60	$70.08	9%	13%	41%	38%
PDSU	5	60	$48.01	7%	10%	53%	30%
Low-Cost Treatment Combination							
WDFP	5	60	$46.75	7%	10%	55%	29%
WDLU	2.5	60	$42.22	4%	9%	59%	27%
PDFP	5	180	$63.06	7%	23%	42%	28%
PDSU	2.5	120	$42.60	4%	14%	58%	24%

a/ Represents annualized cost per ton.

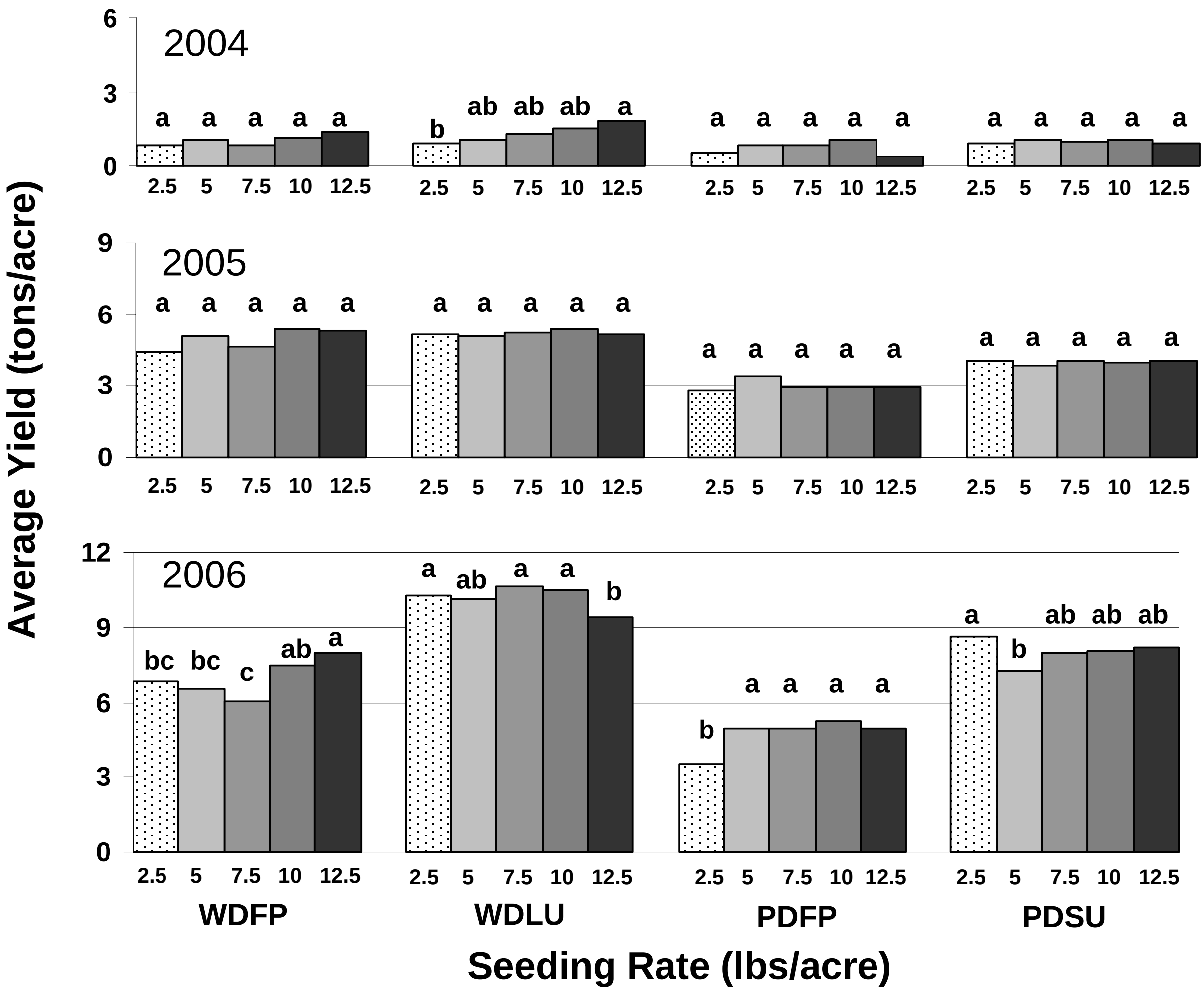

Figure 1. Average switchgrass yields for alternative seeding rate treatments, Milan, TN, 2004-2006.

Notes: Letters separate any two means at *p* =.05 by pairwise comparison for year x environment interactions; WDFP = well drained flood plain, WDLU = well drained level upland, PDFP= poorly drained flood plain, PDSU=poorly drained sloping upland.

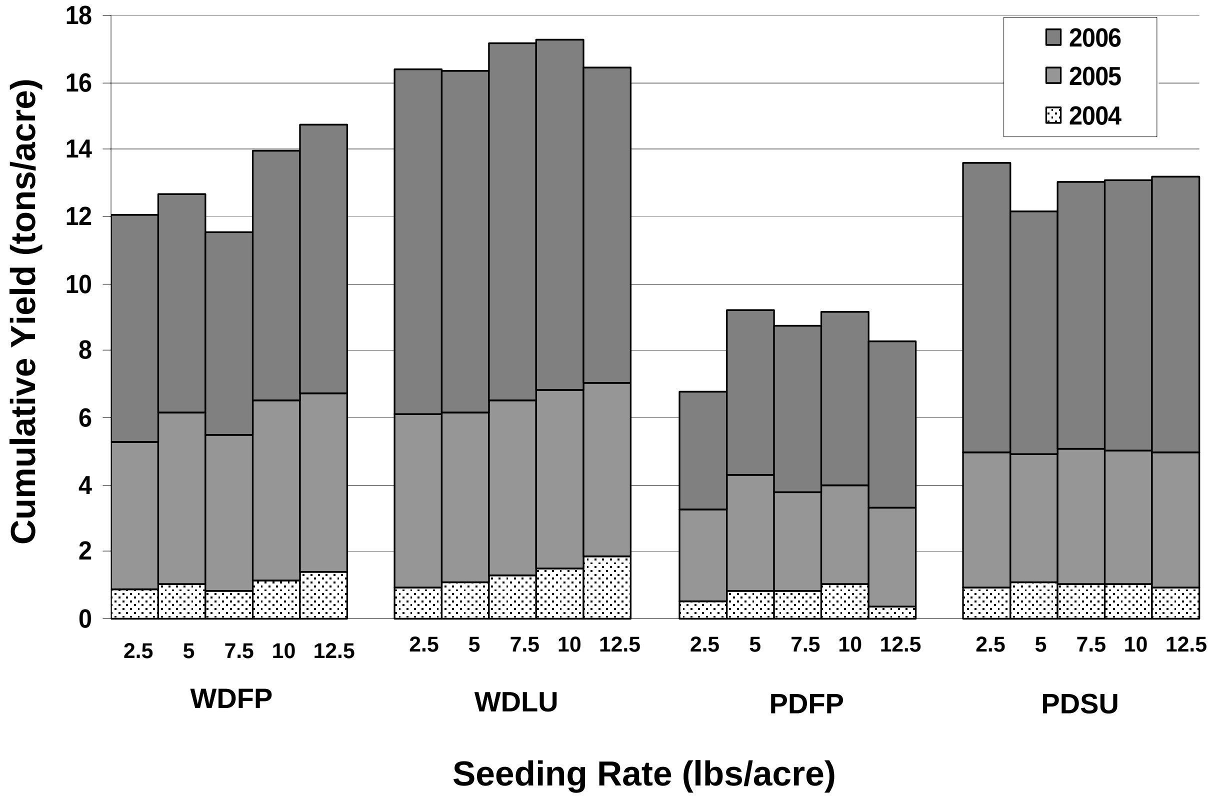

Figure 2. Cumulative switchgrass yields for alternative seeding rate treatments, Milan, TN, 2004-2006.

Notes: WDFP = well drained flood plain, WDLU = well drained level upland, PDFP= poorly drained flood plain, PDSU=poorly drained sloping upland.

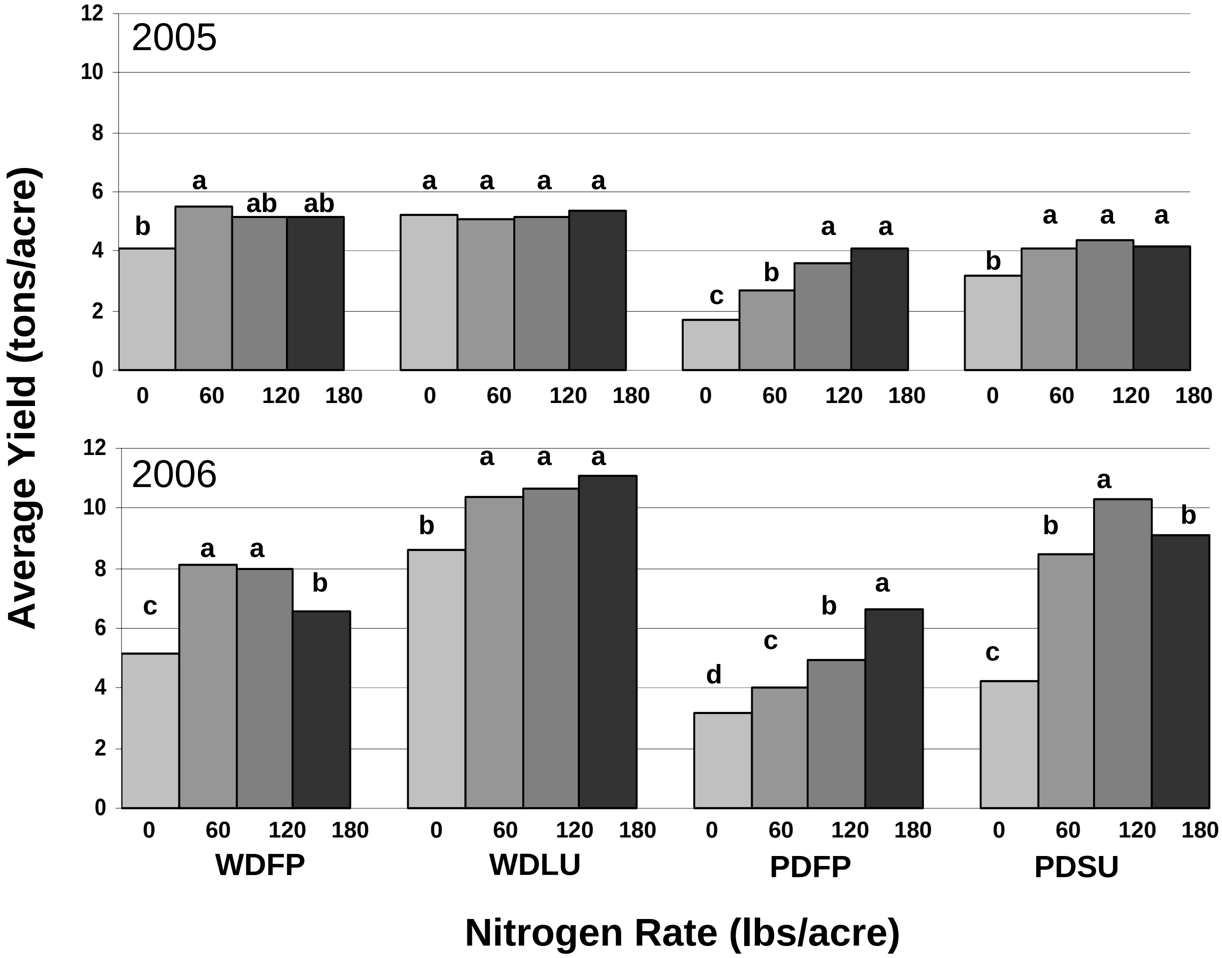

Figure 3. Average switchgrass yields for alternative nitrogen rate treatments, Milan, TN, 2005-2006.

Notes: Letters separate any two means at p =.05 by pairwise comparison for year x environments interactions; WDFP = well drained flood plain, WDLU = well drained level upland, PDFP= poorly drained flood plain, PDSU=poorly drained sloping upland.

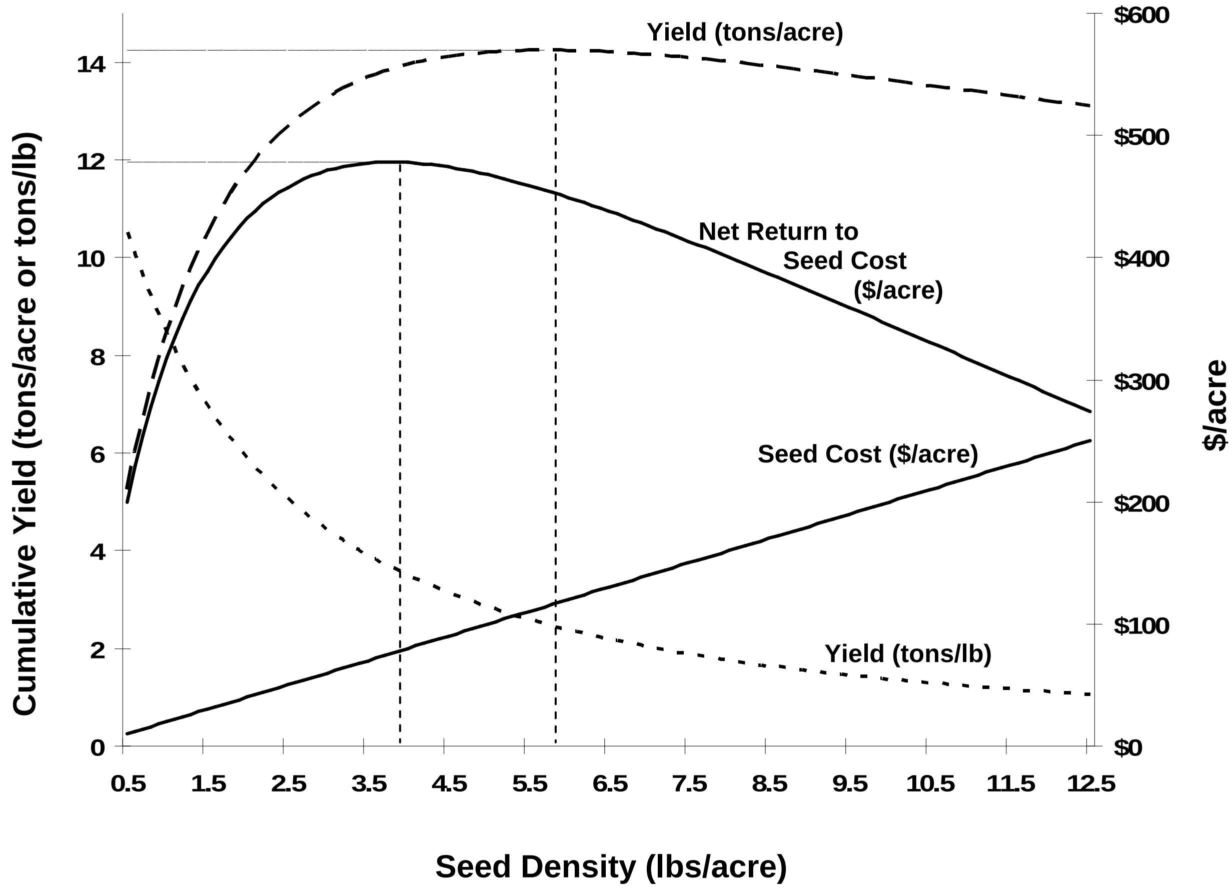

Figure 4. Relationship between cumulative yield, seed density, and net returns in a poorly drained sloping upland (PDSU) production environment, Milan, TN, 2004-2006

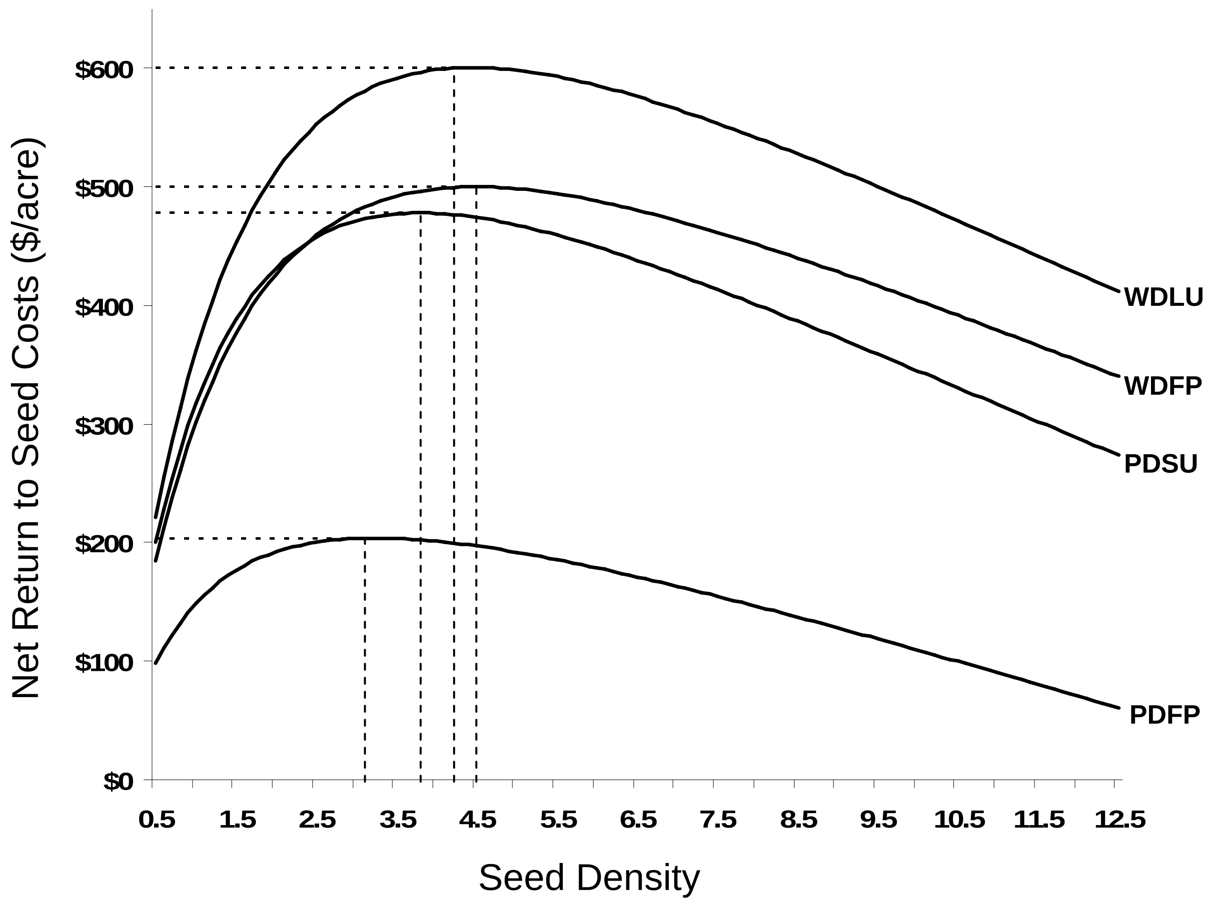

Figure 5. Economically optimal seeding rates by production environment, Milan, TN, 2004-2006

Notes: WDFP = well drained flood plain, WDLU = well drained level upland, PDFP= poorly drained flood plain, PDSU=poorly drained sloping upland.

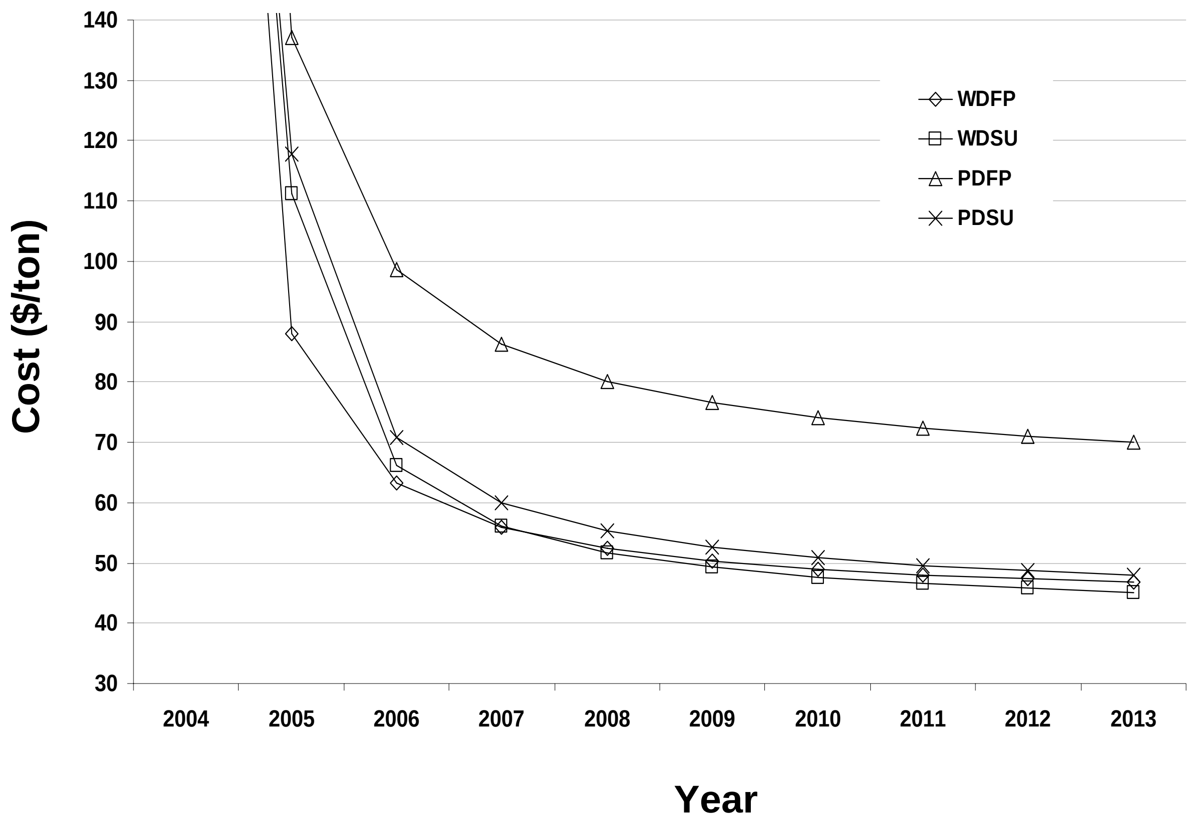

Figure 6. Projected per-ton production, harvest, and loading costs for switchgrass produced as a bioenergy crop for alternative production environments with "typical" input recommendations, West Tennessee, 2004-2013.

Notes: Assumes 5 lbs/acre pure live seed and 60 lbs/acre N. WDFP = well drained flood plain, WDLU = well drained level upland, PDFP= poorly drained flood plain, PDSU=poorly drained sloping upland.

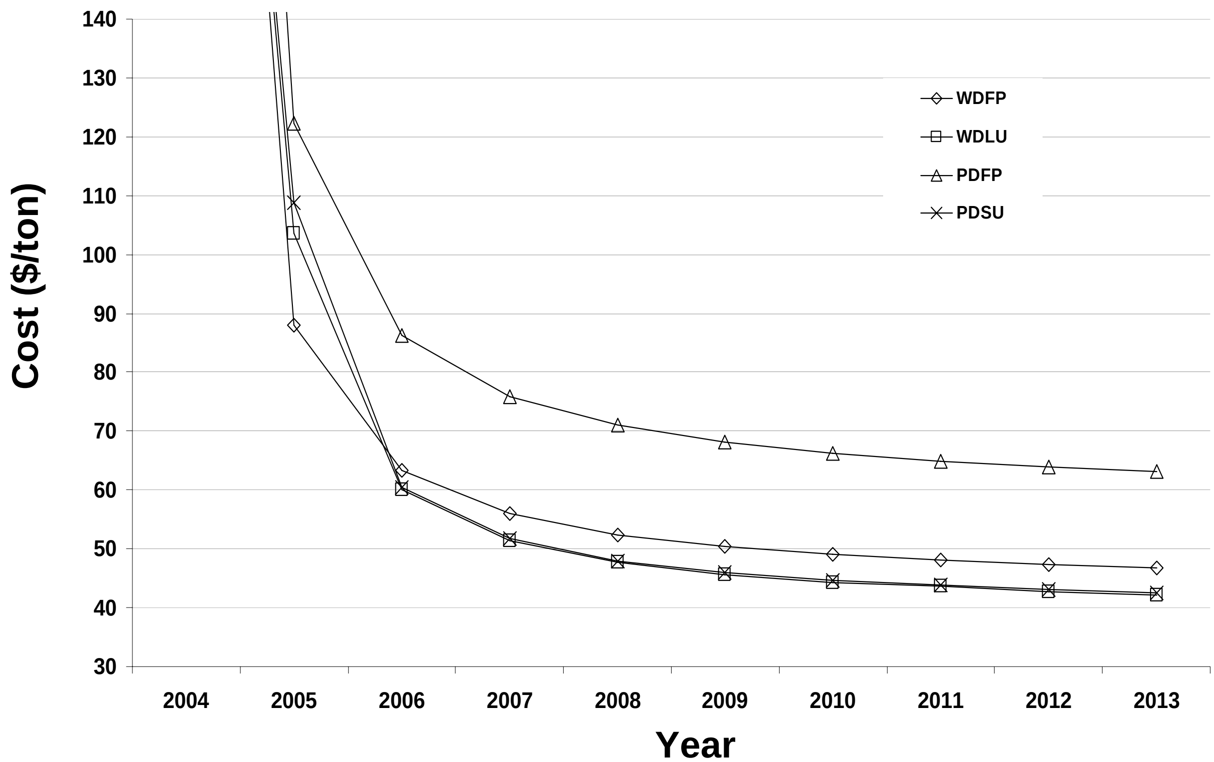

Figure 7. Projected per-ton production, harvest, and loading costs for switchgrass produced as a bioenergy crop for alternative production environments with low-cost treatment combinations, West Tennessee, 2004-2013.

Notes: WDFP = well drained flood plain, WDLU = well drained level upland, PDFP= poorly drained flood plain, PDSU=poorly drained sloping upland. Low-cost treatment combinations are as follows WDFP = 60 lbs N and 5 lbs seed; WDLU = 60 lbs N and 2.5 lbs seed; PDFP = 180 lbs N and 5 lbs seed; PDSU = 120 lbs N and 2.5 lbs seed.