Yield and Breakeven Price of 'Alamo' Switchgrass for Biofuels in Tennessee

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Economic Analysis

ABSTRACT

Research on how land suitability affects yields and breakeven prices for switchgrass (*Panicum virgatum* L.) grown as a bioenergy crop is lacking for the U.S. Southeast. Data from a 3-yr multilocation experiment at Milan, TN, were analyzed to determine the influence of soil drainage and landscape position on switchgrass yield and farm-gate breakeven price. Plots were seeded in 2004 with 'Alamo' at 2.8, 5.6, 8.4, 11.2, and 14.0 kg ha^{-1} pure live seed (PLS). Plots were split in 2005 and N was applied at 0, 67, 134, and 201 kg N ha^{-1}. Farm-gate breakeven prices for 5- and 10-yr production contracts were determined by calculating unit production costs from enterprise budgets that varied by input level and yield. Maximum yields occurred at 67 kg N ha^{-1} on well-drained soils and at higher N levels on less-well-drained soils. Yield response to seeding rate (SR) was insignificant or small relative to other factors. Averaged across treatments, the well-drained upland location suitable for row crops had the largest yield (17.7 Mg ha^{-1}) and lowest breakeven price (\$46 Mg^{-1}) for a 10-yr period. In contrast, the poorly drained flood plain location considered marginal yielded lowest (8.5 Mg ha^{-1}) and had the highest breakeven price (\$69 Mg^{-1}). Breakeven prices were sensitive to yield, N price, and fuel price. Results suggest a lower breakeven price for switchgrass in the U.S. Southeast as compared with other U.S. regions, mainly due to high yields for the Alamo variety.

The selection of switchgrass as a model feedstock for the renewable biofuels industry was based, in part, on the observation that it produces high yields in marginal production environments (McLaughlin and Kszos, 2005). This trait may become particularly valuable in coming years as renewable fuel mandates begin to take effect and concern over the food-versus-fuels debate increases. For example, the Energy Independence and Security Act of 2007 will require 136 billion liters of biofuels to be produced from renewable sources found within the United States by 2022. Just under half of this production is mandated to be derived from cellulosic biomass sources such as switchgrass. It is estimated that up to 16.9 million hectares (about 10% of the U.S. agricultural land base) could become available for cellulosic biomass production depending on market conditions (De La Torre Ugarte et al., 2007). The majority of this area is predicted to come from land considered to be marginal for the production of row crops such as pasture or land currently idled (Perlack et al., 2005); yet research information is lacking on how land suitability affects yields and breakeven prices for switchgrass grown as a bioenergy crop.

Previous agronomic research on the production of switchgrass as a bioenergy crop has addressed optimal N fertilization rates (Lemus et al., 2008; Madakadze et al., 1999; Muir et al., 2001; Thomason et al., 2005; Vogel et al., 2002); harvest timing and frequency (Adler et al., 2006; Fike et al., 2006; Madakadze et al., 1999; Sanderson et al., 1999; Thomason et al., 2005; Vogel et al., 2002); water stress (Sanderson and Reed, 2000; Stout et al., 1988; Stroup et al., 2003); and establishment (Monti et al., 2001; Schmer et al., 2005). Interactions between N and physiogeographic characteristics of the production environment such as soil drainage (well drained vs. poorly drained), landscape position (upland vs. flood plain), and slope (level vs. sloping) are less well understood. Potential interactions between N and SR have also not been previously explored. Nitrogen and seed represent costly inputs, and potential interactions between land suitability, N, and SR may carry considerable economic significance.

Switchgrass production in the U.S. Southeast may have an economic advantage as compared with other U.S. regions, based on higher biomass yields. Recent estimates of switchgrass production costs have focused on upland switchgrass cultivars grown in northern U.S. latitudes, and may not accurately represent expected yield levels and production costs elsewhere. For instance, Duffy (2007) in Iowa calculated the farm-gate breakeven price for switchgrass to be \$90 Mg^{-1} at an 8.96 Mg ha^{-1} yield level.[1] In Illinois, Khanna et al. (2008) estimated a farm-gate breakeven price of \$98 Mg^{-1} for a baseline yield level of 9.42 Mg ha^{-1}. Perrin et al. (2008) report an average

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Published in Agron. J. 101:1234–1242 (2009).
doi:10.2134/agronj2009.0090

[1] Cost estimates reported here include establishment, annual maintenance, and harvest costs, plus the opportunity cost of land for a 10-yr production period.

Abbreviations: MDSU, moderate to somewhat poorly drained eroded sloping upland; PDFP, poorly drained flood plain; PLS, pure live seed; SR, seeding rate; WDFP, well to moderately well drained flood plain; WDLU, moderately well drained level upland.

farm-gate breakeven price of \$59 Mg^{-1} for a sample of 11 producers located in the U.S. Central Plains with average yields of 5.0 Mg^{-1}.

Lowland switchgrass cultivars grown in the U.S. Southeast such as Alamo typically have higher biomass yields than do upland ecotypes produced in more northern latitudes. For instance, Fike et al. (2006) reported an average yield of 12.2 Mg ha^{-1} over 3 yr for stands of mature Alamo switchgrass in West Tennessee. In Texas, Muir et al. (2001) recorded an average yield of 13.4 Mg ha^{-1} for Alamo across two locations at 168 kg N ha^{-1}. Higher yields for the Alamo variety may also translate into lower unit production costs for producers in the U.S. Southeast as compared with producers in more northern U.S. latitudes. This notion is supported by Epplin et al. (2007), who determined a unit production cost of \$56 Mg^{-1} for lowland switchgrass in Oklahoma using secondary yield data. The objective of this research was to compare yields and breakeven prices for Alamo switchgrass produced as a bioenergy crop as influenced by land suitability, SR and N fertilization rate in West Tennessee.

MATERIALS AND METHODS

Experiment Design

Switchgrass yield data from 2004 through 2006 were obtained from a field experiment conducted at the University of Tennessee Research and Education Center at Milan, TN (35°56′ N, 88°43′ W). The experiment was established in 2004 at four locations representing the predominant physiogeographic landscape positions and soil types found in West Tennessee. The locations were (i) a moderately well drained level upland (WDLU), (ii) a well- to moderately well-drained flood plain (WDFP), (iii) a moderate to somewhat poorly drained eroded sloping upland (MDSU), and (iv) a poorly drained flood plain (PDFP). The WDLU and WDFP locations represented high-yielding environments suitable for row crop production. Soil at the WDLU location was predominately Grenada silt loam (fine-silty, mixed, active, thermic Oxyaquic Fraglossudalfs). Soil types at the WDFP location were Vicksburg silt loam (coarse-silty, mixed, active, acid, thermic Typic Udifluvents) and Collins silt loam (coarse-silty, mixed, active, acid, thermic Aquic Udifluenvents).

The less-well-drained MDSU and PDFP locations represented intermediate and marginal yield environments, respectively, and are characteristic of West Tennessee farmland that typically qualifies for the USDA Conservation Reserve Program. The MDSU landscape, in particular, is representative of over half the farmland in West Tennessee, and is considered to be the most likely production environment for switchgrass produced as a bioenergy crop in the region. Soil at the MDSU location was moderately eroded Grenada silt loam with a 6% slope. The soils at the PDFP location were predominately Falaya silt loam (coarse-silty, mixed, active, acid, thermic Aeric Fluvaquents) and Waverly silt loam (coarse-silty, mixed, active, acid, thermic Fluvaquentic Endoaquepts).

Experiments at each location were established in 2004 as a randomized complete block in a strip-plot arrangement with four replications. The SR treatments were 2.8, 5.6, 8.4, 11.2, and 14.0 kg ha^{-1} PLS. Seeding rate main plots measured 29.2 by 4.6 m and were seeded with the Alamo variety using a no-till drill at 19-cm row spacings during the first week of June. Previous research indicates that low levels of P or K do not negatively impact Alamo switchgrass yields in the upper southeastern United States (Parrish et al., 2003). This result is likely due to the efficient translocation of these nutrients into the crown root system during senescence. Soil tests taken before establishment indicated medium to high levels of P at all four locations and medium levels of K at two of the four locations. Low levels of K were found at the MDSU and PDFP locations. Despite the low nutrient requirements for switchgrass produced as a bioenergy feedstock, 89.7 kg P_2O_5 ha^{-1} and 89.7 kg K_2O ha^{-1} were applied to all plots before establishment to partially compensate for nutrient removal in the stem and leaves of harvested biomass. Soil tests also indicated a soil pH of 5.8 or above at all four locations, indicating no need for lime application.

In 2005, blocks were split in strips perpendicular to the SR main plot treatments for N fertilization. Nitrogen application rates were 0, 67, 134, and 201 kg N ha^{-1}. The resulting N main plots measured 22.8 by 7.3 m and the SR × N subplots measured 7.3 by 4.6 m. All subplots in 2006 received N treatments identical to 2005 levels. No N was applied in 2004 to reduce competition from annual weeds during establishment. Plots were harvested annually from 2004 to 2006 following the first killing frost, with specific dates ranging from late October to late November. Soil tests conducted annually indicated that P levels remained medium to high at all four locations; whereas K levels ended low at three of four locations. These tests suggest that maintenance applications of K may be needed for continued switchgrass production over multiple years.

ANOVA Analysis

Dry matter yield data were analyzed for significant differences in SR and N main effects and their interaction from 2004–2006 using a repeated measures strip-plot ANOVA with random replications. Switchgrass is a perennial grass, and yields recorded from the same plots in different years represent repeated measures on the same subject over time. Given that yield outcomes from adjacent years during the establishment phase will be more closely correlated with each other than with yield outcomes from more distant years, we controlled for the possibility of autocorrelation though the specification of an autoregressive covariance structure (Littell et al., 2006). The SR, N, and year (YEAR) were considered fixed effects, while the replications (REP) were considered random effects. The ANOVA model was specified to include separate error terms for the SR and N main effects and the SR × N interaction effect to control for differences in plot sizes used in estimating standard errors.

The mixed model used for this experiment was

$$\mathrm{Y}_{ijkt} = \mu_{ijt} + \mathrm{r}_k + a_{ik} + b_{jk} + c_{ijk} + \mathrm{e}_{ijkt} \qquad [1]$$

where Y_{ijkt} was the observed yield for the kth repeated subplot assigned to the ijth SR × N treatment combination in year t; μ_{ijt} was the mean of the ijth SR × N treatment combination across replications in year t; r_k was a random error term representing replication effects; and the terms a_i, b_j, and c_{ij} represented error terms for the ith SR main effect, the jth N main effect, and the ijth SR × N interaction effect, respectively. The last term e_{ijkt} represented the $ijkt$th subplot error. All error terms were assumed identically and individually distributed.

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

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

where μ was the overall mean, α_i was the ith SR main effect, β_j was the jth N main effect, γ_t was the tth main YEAR effect, and the remaining terms in Eq. [2] represented the complete set of interaction effects among SR, N, and YEAR.

The MIXED procedure in SAS release 9.1 (SAS Institute, 2002) was used to estimate the repeated measures strip-plot ANVOA as specified in Eq. [1] and [2] (Littell et al., 2006; Schabenberger, 2008). The RANDOM statement included the terms REP, SR × REP, N × REP, and SR × N × REP to control for the random and strip-plot error terms. 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. Pairwise mean comparison tests between treatment levels were conducted for each location to explore significant differences among least square means (Saxton, 1998).

Production Budgets

Production budgets were developed for the establishment, maintenance, and harvest of no-till switchgrass produced as a dedicated energy crop. Machinery and labor schedules and baseline input prices used for each budget were obtained from The University of Tennessee Extension switchgrass production budget (Gerloff, 2007). Machinery costs included capital recovery (depreciation and interest), repair and maintenance, fuel and lube, taxes, insurance, and housing; and were calculated using recommended methods found in the American Agricultural Economics Association Commodity Costs and Returns Estimation Handbook (American Agricultural Economics Association, 2000) and the American Society of Agricultural Engineers (2006) standards. Assumptions common to all three budgets were the use of a 150-hp tractor to power farm implements, labor at \$8.50 h^{-1}, a diesel price of \$0.56 L^{-1}, and a nominal interest charge of 8% for 6 mo on annual variable operating costs. We report budget figures (\$ ha^{-1}) here as an intermediate step in determining annualized unit production costs (\$ Mg^{-1}).

Switchgrass no-till establishment costs varied based on SR treatment. Establishment costs were \$371.73 ha^{-1} for 2.8 kg ha^{-1} PLS, \$500.16 ha^{-1} for 5.6 kg ha^{-1} PLS, \$628.61 ha^{-1} for 8.4 kg ha^{-1} PLS, \$757.04 ha^{-1} for 11.2 kg ha^{-1} PLS, and \$885.49 ha^{-1} for 14.0 kg ha^{-1} PLS. Establishment costs were limited to the first year of production, and included machinery and labor time, seed, herbicide, fertilizer, and interest on operating costs. Cost calculations assumed a 16-row no-till drill for planting and an 18-m boom-type sprayer for three preemergence and three postemergence herbicide applications. Seed costs (\$ ha^{-1}) were SR (kg PLS ha^{-1}) multiplied by seed price \$44.10 kg^{-1}. Currently, 44.8 kg P_2O_5 ha^{-1} and 89.7 kg K_2O ha^{-1} are recommended for switchgrass as a bioenergy feedstock when the soil tests low for these nutrients (Garland, 2008). To provide a conservative establishment cost estimate, costs for the recommended rates at \$0.71 kg^{-1} P_2O_5 and \$0.49 kg^{-1} K_2O were included in the budget for each location.[2] None of the plots required reseeding, and thus reseeding costs were not included in establishment estimates.

Annual maintenance costs varied based on nitrogen treatment. Maintenance costs were \$42.55 ha^{-1} for 0 kg N ha^{-1}, \$114.87 ha^{-1} for 67.2 kg N ha^{-1}, \$179.60 for 134.4 kg N ha^{-1}, and \$244.34 for 201.6 kg N ha^{-1}. Maintenance costs accrued in all years except establishment, and included machinery and labor, herbicide, fertilizer, and interest on variable operating costs. Machinery and labor cost calculations assumed a single herbicide spray and fertilizer spreading in early spring. N costs (\$ ha^{-1}) were N treatment level (kg ha^{-1}) multiplied by N price \$0.93 kg^{-1}. Machinery costs were lower for an N rate of 0 kg ha^{-1} due to a reduction in required field operations (i.e., fertilizer spreading). Phosphorus and K costs were included on an annualized basis at recommended rates assuming the soil tests low for these nutrients every 3 yr following establishment. While this assumption appears appropriate for K given the low soil test results, it likely provides a conservative cost estimate for P since soils remained at medium to high levels at all four locations.

Harvest costs were calculated as a function of yield for switchgrass harvested in large round bales (681 kg $bale^{-1}$). Separate budgets were developed for each SR and N treatment combination at each experiment location and for each year of production. Costs included in the harvest budget were for machinery and labor, bale twine, and interest on variable operating costs. Machinery and labor costs included mowing, raking, baling, staging, and loading operations. Based on previous harvest experience through The University of Tennessee Biofuels Initiative, the mowing and raking operations were assumed to function at constant performance rates of 0.18 and 0.08 h ha^{-1}, respectively, for all yield levels. The variable-chamber large round baler used to harvest the switchgrass was assumed to operate at a throughput rate of 4.5 Mg h^{-1}. This assumed rate represents the low end of throughput capacity for similar type balers, and thus provides a conservative estimate of harvest costs. The estimate is also consistent with previous research on alternative cellulosic biofuels crops such as corn stover (Perlack and Turhollow, 2003). The staging and loading operations to transport bales from the field to the farm gate were assumed to operate at a rate of 5.4 Mg h^{-1}. Twine cost (\$ ha^{-1}) was twine price \$1.19 $bale^{-1}$ multiplied by yield level in bales (bales ha^{-1}). Final harvest costs for the year with the largest yields (2006) were highest at the WDLU location, ranging from \$494 to \$770 ha^{-1} for yields of 17.2 to 28.2 Mg ha^{-1}, respectively. In the same year, harvest costs were lowest at the PDFP location, ranging from \$195 to \$468 ha^{-1} for yields of 5.4 to 16.1 Mg ha^{-1}, respectively.

[2] Budgeted P and K rates differed from the rates applied in the experiment because P and K recommendations for switchgrass were not developed until after the experiment was initiated.

A land charge that approximated the cash rental rate for cropland in Tennessee of \$168 ha^{-1} (Tennessee Department of Agriculture, 2007) was included separately to represent the opportunity cost of alternative land uses. Variability and uncertainty in land rental values, yield level, and input prices may influence unit cost estimates. To explore how changes in these variables affect the breakeven switchgrass price, we provide sensitivity analysis on the budgeted values in the *Results and Discussion* section below.

Unit Production Costs

The production of perennial energy crops such as switchgrass results in a flow of production costs and yield benefits across time. Breakeven prices at the farm gate were determined for 5- and 10-yr production contracts by calculating annualized unit production costs (\$ Mg^{-1}). A 10-yr stand lifespan for switchgrass is frequently used in the cost of production literature (e.g., Duffy, 2007; Khanna et al., 2008), and reflects the suggested productive life of the switchgrass stand from an agronomic perspective. A 5-yr lifespan, however, may more appropriately represent the economic lifespan of a switchgrass stand under contract with a biorefinery or other buyer. For example, switchgrass production contracts offered by the University of Tennessee Biofuels Initiative and by the USDA Biomass Crop Assistance Program have terms of 5 yr or less (University of Tennessee, 2008; USDA, 2008). Contracts beyond 5 yr may be viewed as unfavorable due to production risks, uncertainty regarding market fluctuations, or the possibility that release of improved switchgrass seed may result in an optimal replacement interval of <10 yr.

Production costs were annualized by discounting maintenance, harvest, and land costs into their establishment year dollar value and then amortizing across the lifespan of the switchgrass production contract. Costs were discounted using the present value formula

$$\sum_{t=0}^{N-1} C_t \,/\, [(1+r)^t], \qquad [3]$$

where N was the contract lifespan (years), C_t was the cost of production on a land-area basis (\$ ha^{-1}) for year t from the production budgets, r was the discount rate representing the opportunity cost of capital (%), and establishment was assumed to occur at time t = 0. A real discount rate of 5.4% was used based on the American Agricultural Economics Association (2000) recommendation that production processes exceeding 1 yr be discounted on a real basis. The rate was determined by subtracting the 10-yr average inflation rate of 2.6% for the period 1997–2006 (U.S. Department of Labor, 2008) from the nominal interest rate in the University of Tennessee Extension switchgrass production budget (Gerloff, 2007).

The present value of production costs were amortized using the capital recovery formula

$$\text{TPC} \times r/[1 - (1 + r)^{-N}], \qquad [4]$$

where TPC was the present value of total production cost on a land-area basis in 2007 dollars (\$ ha^{-1}), and N and r were as previously defined. Unit production costs (\$ Mg^{-1}) were then calculated as annualized production cost (\$ ha^{-1}) divided by annualized dry matter yield (Mg ha^{-1}). Yields for future production years were projected from 2006 yields in determining unit costs. This assumption is justifiable given that switchgrass stands typically reach maturity by the third year of production (Parrish and Fike, 2005). Production cost estimates reported in the results section are for input levels that approximate typical extension recommendations for switchgrass produced as a bioenergy crop (5.6 kg PLS ha^{-1} and 67 kg N ha^{-1}), and for the SR and N treatment combination that minimized the unit cost of production as determined using the methods above.

RESULTS AND DISCUSSION

Switchgrass Yields

The first objective was to analyze the effect of land suitability and potential interactions between land suitability and N and SR input rates on switchgrass yields. Averaged across SR and N treatment levels, the WDLU location suitable for row crop production produced the largest dry matter yields in 2006 (Table 1). By comparison, the lowest dry matter yields in 2006 (10.55 Mg ha^{-1}) were observed at the PDFP location with marginal land suitability (Table 1). Lower yields for this location were likely due to a combination of land suitability and weed factors given that significant populations of Broadleaf Signal Grass (*Brachiaria platyphylla* L.) and Crabgrass (*Digitaria sanguinalis* L.) were observed to canopy the emerging switchgrass in 2004 and 2005. Averaged across locations and treatment combinations, first and second year yields were 14% and 59% of third year yields, respectively. Yield projections for 5 and 10 yr based on these yield data were consistent with previous Alamo field trials in southern U.S. latitudes (Fike et al., 2006; Muir et al., 2001). Projected annualized dry matter yields by location for the 5-yr (10-yr) contract period by location were 12.43 (12.75) Mg^{-1} yr^{-1} at the WDFP location; 16.82 (17.72) Mg^{-1} yr^{-1} at the WDLU location; 8.24 (8.53) Mg^{-1} yr^{-1} at the PDFP location; and 13.06 (13.80) Mg^{-1} yr^{-1} at the MDSU location.

The ANOVA results indicated the N and YEAR main effects and the N × YEAR interaction effect influenced dry matter yields

Table 1. Switchgrass dry matter yields at four locations averaged across seeding rate and nitrogen fertilization treatments at Milan, TN, 2004 to 2006.

	Experiment location†			
	WDFP	WDLU	PDFP	MDSU
	Mg ha^{-1}			
2004				
Mean	2.37	2.96	1.59	2.22
SD	1.21	1.12	0.81	0.63
Min.	0.83	0.72	0.25	1.25
Max.	4.73	4.91	2.80	3.54
2005				
Mean	11.13	11.65	6.74	8.89
SD	3.05	2.04	2.67	2.44
Min.	4.03	7.84	1.57	3.58
Max.	18.59	18.14	14.34	17.25
2006				
Mean	15.59	22.87	10.55	17.96
SD	6.07	4.08	4.52	6.83
Min.	1.86	12.52	2.31	5.47
Max.	35.35	32.23	20.88	36.00

† WDFP = well to moderately well drained flood plain, WDLU = moderately well drained level upland, PDFP = poorly drained flood plain, and MDSU = moderately to somewhat poorly drained eroded sloping upland.

Table 2. Repeated measures ANOVA results for seeding rate (SR), nitrogen rate (N), and year (YEAR) main effects and their interactions on switchgrass yield at Milan, TN, 2004 to 2006.

Effect	WDFP†		WDLU		PDFP		MDSU	
	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
N	4.53	0.034*	4.51	0.0267*	34.7	<0.0001**	38.18	<0.0001**
SR × N	1.05	0.423	1.31	0.2438	0.59	0.8377	0.70	0.7448
YEAR	327.10	<0.0001**	1431.66	<0.0001**	371.53	<0.0001**	659.38	<0.0001**
SR × YEAR	0.92	0.506	2.08	0.0435*	2.29	0.0253*	0.91	0.5076
N × YEAR	4.72	0.000**	6.98	<0.0001**	13.92	<0.0001**	26.5	<0.0001**
SR × N × YEAR	0.82	0.708	0.74	0.8055	0.31	0.9991	0.82	0.7084

* Significant at the 0.05 level of probability.

** Significant at the 0.01 level of probability.

† WDFP = well to moderately well drained flood plain, WDLU = moderately well drained level upland, PDFP = poorly drained flood plain, MDSU = moderately to somewhat poorly drained eroded sloping upland.

‡ Significant at the 0.10 level of probability.

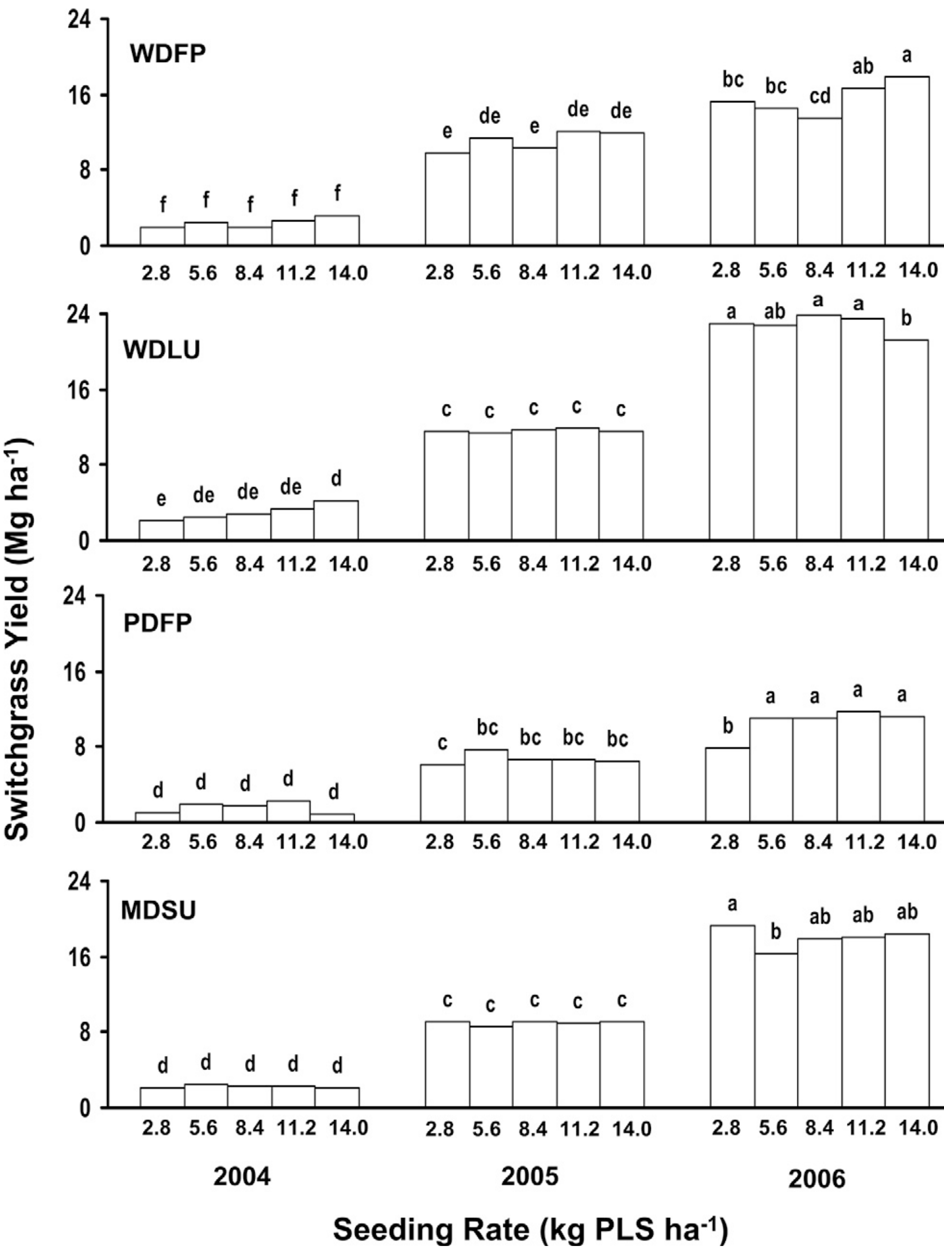

Fig. 1. Average switchgrass dry matter yields at four locations for a range of seeding rate treatments at Milan, TN, 2004 to 2006. Letters separate means within locations at *P* = 0.05 by pairwise comparison; WDFP = well to moderately well drained flood plain, WDLU = moderately well drained level upland, PDFP = poorly drained flood plain, MDSU = moderate to somewhat poorly drained poorly drained eroded sloping upland. PLS = pure live seed.

at all four locations (Table 2). The SR main effect influenced yields at the WDFP and PDFP production locations, and the SR × YEAR interaction term was influential at the WDLU and PDFP locations (Table 2). The SR × N and SR × N × YEAR interaction terms were not significant at any location, which suggests that yield response of switchgrass to SR operates independently of the yield response of switchgrass to N. Based on these findings, paired difference mean comparison tests are reported at the SR × YEAR and N × YEAR interaction levels.

Few significant differences in dry matter yields were observed among SR treatment levels (Fig. 1). With one exception, SR level did not influence switchgrass yields in 2004 and 2005. The exception was the WDLU location, where yields obtained at a rate of 14.0 kg PLS ha^{-1} were 50% higher than for 2.8 kg PLS ha^{-1}. In 2006, yield differences were observed at two locations. At the PDFP location, yields for the 2.8 kg PLS ha^{-1} level were 19% lower than at the 5.6 kg PLS ha^{-1} level. At the WDFP location, switchgrass yields for the 14.0 kg PLS ha^{-1} level were larger than for all SR levels below 11.2 kg PLS ha^{-1}. The absence of a significant and consistent yield response to SR across locations suggests that, even at low SR levels, sufficient plant population densities were obtained to reach the establishment threshold, after which there is no response to increased SR (Vogel and Masters, 2001; Schmer et al., 2005).

The influence of N on switchgrass dry matter yields was more evident (Fig. 2). In 2005, yield increased with N at three of four locations. At the WDFP and MDSU locations, yields at 67 kg N ha^{-1} were larger than for 0 kg N ha^{-1} by 25% and 22%, respectively. At the PDFP location, yield increased for all N levels up to 134 kg N ha^{-1}. The exception was for the WDLU location, which had the highest overall average yields but no response to N. In 2006, yield maximums at the two well-drained locations, WDFP and WDLU, were obtained at the 67 kg ha^{-1} treatment level. At the two less-well-drained locations, MDSU and PDFP, yield maximums were obtained at 134 and 202 kg N ha^{-1} treatment levels, respectively. While relatively high N levels may be optimal for the period of analysis, Parrish et al. (2003) caution that the continued application of N at relatively high levels may decrease yields in later years by thinning stands due to decreased tillering. Both the WDFP and the MDSU locations showed a significant decrease in yield between the 134 and 202 kg N ha^{-1} levels, suggesting a parabolic relationship for switchgrass yield response to N. Conversely, yield response at the PDFP location appeared linear. The finding of differences in yield response at different locations is consistent with Muir et al. (2001), who report a quadratic response to N for Alamo switchgrass in a fine sandy loam soil in Stephenville, TX, but a linear response switchgrass in a sandy clay loam at Beeville, TX.

Breakeven Farm-Gate Prices

The second objective was to determine farm-gate breakeven prices for switchgrass produced as a dedicated energy crop. The farm-gate breakeven price is the switchgrass price that would allow the producer to just cover all costs of production, including the opportunity cost of alternative land uses. Unit production costs for 5- and 10-yr production contracts were calculated for each location based on production budgets (Table 3). Breakeven farm-gate prices for switchgrass grown under a 5-yr contract following typical extension recommended input levels ranged from \$52.99 Mg^{-1} at the high-yielding WDLU location suitable for row crop production to \$78.88 Mg^{-1} at the low-yielding PDFP location with marginal land characteristics that also had severe weed infestation (Table 3). Harvest costs represented the largest cost component. For all locations except the PDFP location, harvest costs contributed to over half (>50%) the final cost estimates. Land costs were the next largest cost component making up just under 25% of final costs. Establishment and maintenance costs represented the smallest cost components, at just over 10% each. Under a 10-yr contract, breakeven prices for switchgrass produced using typical extension recommendations ranged from \$5.70 Mg^{-1} to \$10.28 Mg^{-1} lower than for the 5-yr contracts at the high-yielding WDLU location and the low-yielding PDFP location, respectively (Table 3). The cost-minimizing treatment combinations differed from extension recommended input levels for all but the WDLU location; indicating that cost reduction may be possible through improved input management. For instance, unit costs were minimized at the 5.6 kg PLS ha^{-1} level at the two flood plain locations but at 2.8 kg PLS ha^{-1} for the two upland locations. By contrast, unit costs were minimized at 67 kg N ha^{-1} at the well to moderately well drained locations but at higher rates for the two less-well-drained locations.

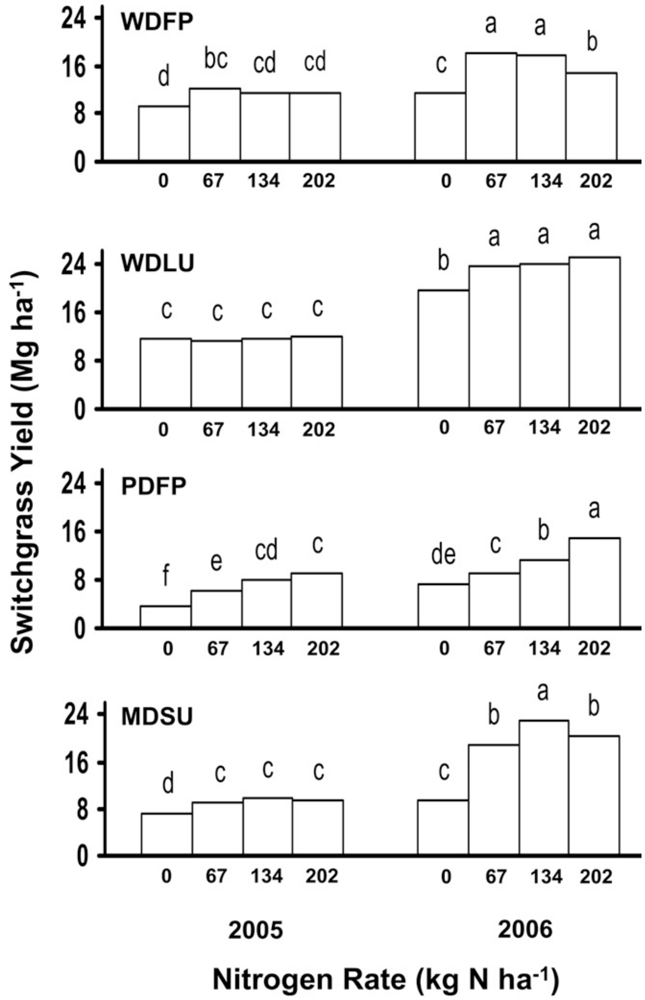

Fig. 2. Average switchgrass dry matter yields at four locations for a range of nitrogen fertilizer treatments at Milan, TN, 2005 to 2006. Letters separate means within locations at *P* = 0.05 by pairwise comparison; WDFP = well to moderately well drained flood plain, WDLU = moderately well drained level upland, PDFP = poorly drained flood plain, MDSU = moderately to somewhat poorly drained eroded sloping upland.

The 10-yr breakeven price estimates reported here compare favorably to similar studies recently conducted in Illinois (\$98 Mg^{-1}) by Khanna et al. (2008) and in Iowa (\$90 Mg^{-1}) by Duffy (2007) in Iowa. Even at the low-yielding PDFP location, breakeven prices in West Tennessee remained approximately \$21 and \$29 Mg^{-1} lower than the Illinois and Iowa studies, respectively. This disparity is primarily due to differences in yield estimates used to calculate unit costs. Yields assumed for the upland switchgrass variety used in the Illinois and Iowa studies were close to 9 Mg ha^{-1}, as compared with the 10-yr average yield projection of up to 17.7 Mg ha^{-1} reported here for the lowland Alamo variety. The 5-yr cost estimates reported here are similar to those reported by Perrin et al. (2008) for farm-scale switchgrass trials conducted in Nebraska, South Dakota, and North Dakota. In this case, production costs were comparable because the cost disadvantage associated with lower average yield levels in the Perrin et al. study (from 3.8 to 7.9 Mg ha^{-1}) was offset by lower harvest costs. Our findings

Table 3. Five- and 10-yr breakeven prices at the farm gate for switchgrass grown as a bioenergy crop at four locations at Milan, TN, 2004 to 2006 (2007 U.S. Dollars).

Location	Seeding rate	Nitrogen rate	Annualized unit production cost				Breakeven price
			Establishment	Maintenance	Harvest	Land	
	kg ha^{-1}		$ Mg^{-1}				$ Mg^{-1}
5-yr breakeven price, typical extension recommendation							
WDFP†	5.6	67	7.28	5.87	29.07	11.03	53.25
WDLU	5.6	67	7.21	5.82	29.04	10.93	52.99
PDFP	5.6	67	13.99	11.28	32.42	21.20	78.88
MDSU	5.6	67	8.06	6.51	29.46	12.22	56.25
5-yr breakeven price, cost-minimizing treatment combination							
WDFP	5.6	67	7.28	5.87	29.07	11.03	53.25
WDLU	2.8	67	4.98	5.41	28.78	10.15	49.32
PDFP	5.6	202	9.78	16.79	30.32	14.83	71.73
MDSU	2.8	134	4.51	7.66	28.47	9.20	49.83
10-yr breakeven price, typical extension recommendation							
WDFP	5.6	67	3.58	5.75	28.60	9.61	47.54
WDLU	5.6	67	3.41	5.46	28.45	9.13	46.45
PDFP	5.6	67	7.00	11.23	31.62	18.76	68.60
MDSU	5.6	67	3.83	6.14	28.82	10.26	49.04
10-yr breakeven price, cost-minimizing treatment combination							
WDFP	5.6	67	3.58	5.75	28.60	9.61	47.54
WDLU	2.8	67	2.33	5.02	28.20	8.39	43.93
PDFP	5.6	202	4.80	16.38	29.68	12.88	63.74
MDSU	2.8	134	2.09	7.04	27.92	7.53	44.58

† WDFP = well to moderately well drained flood plain, WDLU = moderately well drained level upland, PDFP = poorly drained flood plain, MDSU = moderately to somewhat poorly drained eroded sloping upland.

are also consistent with Epplin et al. (2007), who report a unit production cost of $56 Mg^{-1} for the southern Plain states for lowland Alamo type switchgrass cultivars.

These results suggest that the production of switchgrass as a bioenergy crop in the U.S. Southeast may have a distinct advantage over other U.S. regions in terms of production costs based on the yield differences observed between lowland and upland switchgrass ecotypes. Furthermore, production costs in the U.S. Southeast may be further reduced as harvest efficiency increases. At present, forage producers in Tennessee rely primarily on round hay baling equipment. Harvest cost reduction is a realistic near-term goal given that harvest systems based on large, rectangular bales have significantly lower unit costs than do round bale harvest systems (Thorsell et al., 2004). For all locations, the unit cost of production was below the $83 Mg^{-1} refinery-level breakeven price for delivered feedstock set by the University of Tennessee's technology partner in developing a demonstration-scale cellulose-to-ethanol conversion facility (English et al., 2008). The remaining difference between the farm-gate breakeven price and plant-level price paid represents the spread available to cover costs for storage and transportation and returns to producer profit and risk.

Table 4. Sensitivity analysis of 10-yr breakeven prices for switchgrass grown as a bioenergy crop at the moderate to somewhat poorly drained eroded sloping upland (MDSU) location at Milan, TN.

Scenario	Breakeven price	Change from base scenario†
	$ Mg^{-1}	%
Change in average yield from 13.8 Mg ha^{-1}		
25% increase	$44.34	–9.6
25% decrease	$56.93	16.1
Change in seed price from $44.10 kg^{-1}		
50% decrease	$48.08	–2.0
50% increase	$50.05	2.1
Change in N price from $0.93 kg^{-1}		
100% increase	$52.52	7.1
200% increase	$55.98	14.2
Change in P price from $0.71 kg–1 and K price from $0.49 kg^{-1}		
100% increase	$49.94	1.8
No P application	$48.70	–0.7
Change in diesel fuel price from $0.56 L^{-1}		
50% increase	$52.57	7.2
100% increase	$56.26	14.7
Change in discount rate from 5.4%		
Increase to 10%	$50.44	2.9
Increase to 15%	$52.10	6.2
Change in land rental cost from $168 ha^{-1}		
20% decrease	$47.01	–4.1
20% increase	$50.28	2.5

† Base breakeven price for the MDSU location was $49.04 Mg^{-1}.

Sensitivity Analysis

We performed sensitivity analysis on the farm-gate breakeven price for switchgrass grown at the MDSU location under a 10-yr contract at typical extension recommended input levels (Table 4). The MDSU location represents the most likely production environment for switchgrass produced as a bioenergy crop in West Tennessee due to its availability and marginal land characteristics such as slope and shallow depth to root restrictive frangipan. Average switchgrass yields will likely increase in coming years as concerted breeding efforts continue. A 25% increase in average dry matter yields above the base scenario yield would decrease the breakeven price by just less than 10% (Table 4). Conversely, a 25% decrease in yield would increase the breakeven price by over 15%. Increases in fuel and N fertilizer prices may also affect final switchgrass breakeven prices. For instance, either a doubling of the fuel price to $1.12 L^{-1} or a tripling of the N price to $2.79 kg^{-1} would increase the breakeven price by over 14%.

Changes in seed price, land rental price, and P and K prices had less of an influence on the farm-gate breakeven price. Modest price increases for seed (50%), land (20%), or P and K (100%) all resulted in a breakeven price increase of 2.5% or less (Table 4). Finally, changes in the discount rate may also affect the breakeven price, particularly under the 10-yr contract where perceived risks may be higher. While an increase in discount rate to 15% increased the breakeven price, it remained $4.15 Mg^{-1} below the MDSU breakeven price under a 5-yr contract at the baseline discount rate.

Sensitivity analysis was also performed to compare land costs across locations. The opportunity cost of land varies with land productivity. Lower land costs at less productive locations will partially compensate for lower yields and may result in a lower breakeven price as compared with more-productive locations with higher land costs. For example, while the land charge of $168 ha^{-1} applied in the analysis represents the average rental rate for cropland in Tennessee, this figure is likely to be higher at the WDFP and WDLU locations suitable for row crops and lower at the MDSU and PDFP locations with marginal land characteristics. For each location, we determined the reduction in land rental rate required to equate the breakeven price for that location with the baseline breakeven price of $46.45 Mg^{-1} at the WDLU location. At the WDFP location, where yields were similar to the WDLU location, a rental rate reduction of 2.4% to $164 ha^{-1} was sufficient to equalize breakeven prices. At the MDSU location, a 25.2% reduction in the land rental rate to $126 ha^{-1} was required to equalize breakeven prices. For the PDFP location, a total reduction in land rental rate was insufficient to equalize breakeven prices. Even at a land rental rate of $0 ha^{-1}, the PDFP breakeven price remained $3.41 Mg^{-1} higher than the baseline WDLU breakeven price. These findings suggest that the MDSU location may be cost competitive with more productive locations when reduced land rental rates are available.

CONCLUSIONS

This research compared yields and farm-gate breakeven prices for Alamo switchgrass as influenced by land suitability, SR, and N fertilization at four locations in West Tennessee. Dry matter yields and optimal N rates were found to vary by experiment landscape position and soil drainage characteristics. Averaged across treatments, 5-yr projected yields were highest at the WDLU location suitable for row crop production (16.82 Mg ha^{-1}) and lowest at the PDFP location with marginal land characteristics and where significant weed infestations were observed during establishment (8.24 Mg ha^{-1}). Maximum dry matter yields at locations with well-drained soils occurred at 67 kg N ha^{-1}. In contrast, maximum dry matter yields at locations with less-well-drained soils occurred at an N rate of 134 kg N ha^{-1} or above; however, the potential long-term effects of continued application of relatively high N levels on decreased tillering and reduced yields were not considered. The effect of SR on switchgrass yields was insignificant or small relative to N fertilization. Farm-gate breakeven prices for 5- and 10-yr production contracts were determined from enterprise budgets that varied by input level and yield. Baseline breakeven prices for a 10-yr contract where the opportunity cost of land was held constant ranged from $46 Mg^{-1} at the WDLU location to $69 Mg^{-1} at the PDFP location. The breakeven price for the MDSU location most prominent in West Tennessee was $49 Mg^{-1}; however, this location becomes cost competitive with a 25% reduction in land cost relative to the WDLU location. Overall, harvest cost was the largest cost component (>50%), suggesting that increased harvest efficiencies may significantly reduce breakeven switchgrass prices in West Tennessee. Breakeven prices were most sensitive to changes in yield, N price, and fuel price. Breakeven prices for 5-yr contracts were $5.70 Mg^{-1} to $10.28 Mg^{-1} higher than for the 10-yr contract. The 5- and 10-yr cost estimates are lower than or equivalent to previous estimates for other U.S. regions. These findings suggest that switchgrass production in the U.S. Southeast may provide considerable cost advantages in the development of a cellulosic biomass feedstock supply chain for the emerging U.S. ethanol industry.

ACKNOWLEDGMENTS

The authors thank Dr. Blake Brown and the staff at the Milan Research and Education Center, Milan, TN, for field research support. They also thank Dr. Arnold Saxton for helpful comments on the statistical model, and three anonymous reviewers for comments on an earlier draft. The research was made possible with partial funding from the Department of Energy project number DE-FG36-04GO14219, the UT Switchgrass Demonstration Project, and the CSREES/USDA through Hatch Project TEN00348.

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