Is Switchgrass Yield Response to Nitrogen Fertilizer Dynamic? Implications for Profitability and Sustainability at the Farm Level

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Abstract: This paper tests the hypothesis that switchgrass yield response to nitrogen fertilizer is dynamic. Yield and weather data from a five-year experiment in western Tennessee are used. Implications of such a finding on the profitability and sustainability of switchgrass production at the farm level are discussed.

Keywords: Biomass, Energy Crops, Sequential Inputs, West Tennessee

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Introduction

Recent high prices for petroleum-based transportation fuels in the United States have peaked interest in alternative fuel sources. Yet, expansion of the U.S. corn ethanol industry to meet this demand has been met with criticism. For instance, concerns have been raised about the impact of the corn ethanol industry on food prices (Senauer), net energy requirements (Tilman et al.), and environmental impacts such as nutrient contamination (Donner and Kucharik) and the loss of biocontrol services that regulate agroecosystems (Landis et al.).

These drawbacks have spurred interest in cellulosic biomass as a new source of ethanol feedstock. Example sources of cellulosic biomass include warm-season perennial grasses, forest residues, and crop stover. Cellulosic biomass is viewed by many as a desirable ethanol feedstock because it does not compete for land with traditional food crops (e.g., it can be grown on marginal land, or is obtained as a byproduct of crop production), has a favorable net energy balance, and requires fewer inputs than traditional crops. According to the renewable fuels mandate, ethanol derived from cellulosic biomass sources is expected to be the fastest growing industry segment. For instance, the Energy Independence and Security Act of 2007 will require 36 billion gallons of biofuels to be produced from renewable sources by 2022.

Switchgrass (*Panicum Virgatum* L.) is a perennial, warm-season grass species widely recognized for its potential as an herbaceous bioenergy crop. For instance, switchgrass is particularly adept at producing high yields in marginal soils yet requires less management intensity and fewer chemical inputs than traditional row crops (McLaughlin and Kszos). When produced for biomass it can be harvested once in the fall following senescence, thereby allowing nutrients to move from the above ground biomass into the root system and minimizing the need for their replacement (Parrish and Fike). Additional attributes such as enhanced soil conservation, reduced chemical runoff and leaching, and reduced on-farm energy requirements also make switchgrass production attractive from a sustainability perspective (McLaughlin and Kszos).

If mandated cellulosic ethanol benchmarks are to be met, the production of millions of tons of cellulosic biomass such as switchgrass will be required. 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.). 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.). In particular, switchgrass may hold a competitive advantage in the southeastern United States where growing seasons are longer and yields for traditional crops such as corn and soybeans are lower as compared to other U.S. regions (English et al.; Mooney et al.).

The perennial nature of switchgrass suggests that management decisions made during one production period may affect yield outcomes observed in future production periods. For example, switchgrass fertility research sponsored by Oak Ridge National Lab (ORNL) over ten years found that stands receiving high nitrogen (N) fertilization levels (90 lbs/acre) and harvested once in the fall tended to thin out over time (Fike et al.; Parrish et al.). Increased lodging, decreased tiller density, and reduced stand vigor were also observed for these stands. Based on these results, the authors hypothesize that high N rates may maximize short-term yields but reduce long-term yield potential and recommend that N fertilizers be used at limited rates to ensure long-term stand survival. While this hypothesis suggests that switchgrass yield response to N may be dynamic, it has yet to be tested empirically.

The objectives of this paper are to (i) determine the dynamic properties of switchgrass yield response to N fertilizer, and (ii) evaluate the implications of these properties on the profitability and sustainability of switchgrass at the farm level. Profit-maximizing producers will elect to apply N at rates above the levels recommended by Fike et al. and Parrish et al. if they perceive the value of biomass yield gain to exceed fertilizer costs. However, previous research on economically optimal N rates for switchgrass production is limited and does not consider the potential negative effects of sustained N application at high rates on switchgrass net returns. The failure to control for these factors may result in suboptimal N input recommendations. Indeed, the cost of this misspecification in terms of both producers' bottom line and detriment to the environment from over fertilization may be large.

The remainder of this paper is organized as follows. We begin with brief review of the existing switchgrass yield response literature. Next, we develop a dynamic input decision framework based using stage-level production functions. In the third section we specify an empirical yield response model to test whether the slop of the response function changes over time. Finally, we explore the dynamics of switchgrass yield response and then finish by discussing the implications of our findings on profitability and sustainability at the farm level.

Switchgrass Yield Response to Nitrogen Fertilizer

A growing body of research examines the yield response of switchgrass to N fertilization. One strand of this literature explores the minimal level of applied N needed to ensure stand survival. For instance, both Fike et al. and McLaughlin and Kszos observe that applied N at rates of 90 lbs/acre/year or below is adequate for a single harvest system. However, they note that such levels are generally insufficient to replace the quantity of N removed in the harvested biomass. The ability of switchgrass plantings to remain viable at low levels of applied N (i.e., below the removal rate) is generally attributed to improvements in soil structure and productivity that occur over the long term (Parrish and Fike). Factors cited to explain this phenomenon include a superior ability to scavenge existing soil N, efficient nutrient translocation during senescence, the accelerated mineralization of soil organic matter due to the extensive root system, symbiotic relationships with soil and plant microbes and atmospheric deposition (Fike et al.; McLaughlin and Kszos).

A second strand of literature discusses the level of applied N required to maximize switchgrass yields. Such studies indicate that yield maximums may occur at rates of up to 200 lbs/acre or higher for a single harvest system depending on location characteristics. For instance, both Muir et al. and Mooney et al. found 'Alamo' switchgrass yields to respond linearly up to 180 lbs/acre N in less well drained soils but only 60 lbs/acre on well drained soils. However, neither of these studies included data beyond the fourth year nor did they consider the potential negative effects of sustained application of N at high rates over time. Lemus et al. conducted yield response trials in large fields of established switchgrass and found that N rates of 200 lbs/acre maximized yields. They also observed that the effect of N tended to increase over time, reporting that "the beneficial effects of nitrogen are continuing and increasing." This lends yet further evidence to suggest yield response may be dynamic with respect to the N fertilization decision.

Profit-maximizing producers will elect to apply N at rates above the minimum recommended levels for sustainability if they perceive the value of biomass yield gain to exceed fertilizer cost. Previous research on economically optimal N rates for switchgrass production is limited. Haque et al. in Oklahoma estimated a switchgrass yield response function averaged over three years using various functional forms and found economically optimal N rates for a single harvest system to vary between 0 and 60 lbs/acre for the range of N prices (\$0.20 to \$0.70/lb) and biomass prices (\$27 to \$45/ton) considered.

None of the aforementioned studies considered the potential carry over effects (e.g., stand thinning, increased lodging) of N on subsequent future net returns. Thus, it remains to be analyzed whether the sustained application of N at rates above those recommended by Fike et al. and McLaughlin and Kzsos may be more or less profitable in the long run, and what the implications of such a decision would be in terms of yield dynamics, the producer's bottom line, and potential impacts on the environment. This article aims to provide an empirical investigation into these issues.

Forage crop yields are generally assumed to increase annually during an establishment phase, and then stabilize once the stand becomes fully mature. It is frequently assumed with switchgrass that stands reach full maturity by their third year of production (Parrish and Fike). An empirical investigation into the dynamics of switchgrass yield response must account for this physiological property. The appropriate functional form for a time trend variable in an empirical yield model would allow for time to exert a positive but diminishing influence on yield until full maturity is reached, and remain constant thereafter.

Climatic factors are an additional important consideration for determination of crop yield response functions. While the relationship between these factors and crop yields are complex, Hargreaves notes that soil moisture availability is perhaps the most useful in explaining annual variations. Soil moisture availability, in turn, is influenced by many factors including precipitation, temperature, solar radiation, humidity, wind, and crop and land management. Empirical measures of climatic influence amenable to econometric model building focus primarily on the concept of evapotranspiration (Doll; Oury). Evapotranspiration is a combined measure of evaporation from the soil surface and transpiration from plant surfaces and serves as an indicator of soil moisture availability.

Oury succinctly summarizes a number of evapotranspiration formulas and approximations, including the Thornthwaite Ratio, Lang Factor, and the de Martonne and Angstrom Indices and discusses their potential for inclusion in crop response models. Whereas the Thornthwaite ratio depends on a direct measurement of potential evapotranspiration, the remaining approximations are more parsimonious, requiring only precipitation and temperature. Due to the expected annual variations in switchgrass yields due to weather conditions, it will be prudent to control for exogenous climatic factors when isolating the influence of N rate, location characteristics, and time on yields.

Conceptual Framework

To explore these issues further we develop a multi-period sequential input decision framework for analyzing the profit-maximizing producer's N input decision problem. In a single-period model of profit maximization, an agricultural producer applies N until its marginal value product (MVP) equals its marginal factor cost (MFC). However, in a multi-period model, this decision rule does not hold because the effect of current input decisions on future yields must also be considered. Producer expectations of an N carry over effects on subsequent yield outcomes (e.g., stand thinning, increased lodging) may result in more or less N applied than would be suggested by a single period or average response framework.

The profit-maximizing N input decision for switchgrass produced for bioenergy can be viewed as a dynamic optimization problem. As is generally recommended for growing switchgrass as a bioenergy crop, we assume a single fall harvest following senescence (Parrish and Fike). During senescence nutrients from the leaves and stems of the above ground biomass are recycled back into the crown root system, thus minimizing the removal of these nutrients during harvest.

The producer's choice of annual N fertilization rate is assumed to solve the following set of equations:

(1) $$\underset{x_1,..,x_t}{\text{MAX}}\, \mathrm{E}[NR] = \sum_{t=0}^{n} \mathrm{E}[p_t y_t - r_t x_t],$$

(2) $$Y_t = \sum_{t=0}^{n} y_t ,$$

(3) $$p_t = \frac{P_t}{(1+i)^t} \text{, and}$$

(4) $$r_t = \frac{R_t}{(1+i)^t},$$

where *NR* is the present value of cumulative net return to the N fertilization decision over *n* years of production ($/acre), Y_t is cumulative switchgrass yield over *n* years of production, y_t is annual switchgrass yield in year *t* of production, p_t is discounted switchgrass price ($/dry ton), r_t is discounted N cost ($/lb), x_t is N fertilization rate (lbs/acre). All other costs are assumed to be fixed with respect to the N fertilization decision. Input and output prices are discounted as in Equations 3 and 4 using the term $(1+i)^t$ where *i* is the discount rate. Establishment is assumed to occur at time t=0 with the first N application at time t=1.

As suggested by Antle and Hatchett (1986) for perennial forage crops, the potential effect of N fertilization ($x_1, \ldots, x_t$) on cumulative switchgrass yield can be represented by the stage-level production functions:

(5) $$Y_0 = f_0(\theta_0),$$

(6) $Y_1 = f_1(x_1, Y_0, \theta_1)$, and

(7) $Y_t = f_t(x_t, Y_{t-1}, \theta_t)$ for t = 2, 3, . . . , n,

where x_t and Y_t are as previously defined and θ_t represents exogenous events (e.g., location or weather outcomes) that occur in year *t* after the N fertilization decision is made. Notably, equation 7 states that the cumulative switchgrass yield observed for a particular stand in year *t* is a function not only of the N input decision for the same year but also the N input decisions in previous years.

To see how the input decision in one year may affect outcomes in later periods, consider selection of the optimal N level at time *t*=1 for switchgrass produced under a 3-year contract with a biorefinery, not counting the establishment year (t=0). The first order condition for profit maximization is:

$$(8) \qquad \mathrm{E}\left[p_1 \times \frac{\partial Y_3(x_3, Y_2, \theta_3)}{\partial x_1}\right] - \mathrm{E}\left[\frac{\partial C(x_1, x_2, x_3)}{\partial x_1}\right] = 0,$$

where *C* represents the input cost function. Equation (8) can be further simplified as

$$(9) \qquad \mathrm{E}\left[p_1 \times \left(\frac{\partial Y_3}{\partial x_1} + \frac{\partial Y_3}{\partial x_2}\frac{\partial x_2^*}{\partial x_1} + \frac{\partial Y_3}{\partial x_3}\frac{\partial x_3^*}{\partial x_1}\right)\right] = \mathrm{E}\left[r_1 + r_2\frac{\partial x_2^*}{\partial x_1} + r_3\frac{\partial x_3^*}{\partial x_1}\right]$$

after the recursive substitution of Y_2 and Y_1 into Y_3 and application of the chain rule.

As summarized by Antle and Hatchett, the equality in Equation (9) states that the profit-maximizing N rate occurs where the expected value of the marginal product *E*(*VMP*) equals the expected marginal factor cost *E*(*MFC*). The partial derivatives in the left-hand side term include the direct effect of N on cumulative switchgrass yield plus a carryover effect on future years. The right-hand side term includes current input cost, plus an opportunity cost for future production stages. The carryover effect and opportunity cost arise because input use in period *t*=1 may affect future yield potential of the switchgrass stand (e.g. thinning of the stand due to high N rates). If switchgrass yields are indeed dynamic, the carryover and opportunity cost effects imply that the economically optimal N rates for individual years may differ from a singular economically optimal N rate as determined over the entire productive lifetime of the switchgrass stand.

Methods

Empirical modeling generally involves the selection of a functional form to represent particular physical and economic relationships (Griffin et al.). While their true representation is never known, the researcher must select an appropriate functional form to approximates the desired relationship. Selection of this form may be based on decision criteria that include maintained hypotheses, estimation properties, and relevance to a particular dataset or application. Previous studies have shown switchgrass to increase linearly or at a decreasing rate with applied N up to 200 lbs/acre depending on location characteristics. An empirical yield model to capture these possible response patterns while also controlling for climatic conditions is:

$$(10) \qquad y_k = \beta_0 + \beta_1 x_k + \beta_2 x_k^2 + \alpha A_k + e$$

where y_k is yield at location k, x_k is N treatment level, A is the Angstrom Index value, e is an error term assumed to be normally distributed, and the βs and α are parameter coefficients on the N rate and Angstrom Index variables, respectively.

The Angstrom Index controls for the effect of climatic factors on switchgrass growth:

$$(11) \qquad A = \frac{R}{1.07^M},$$

where A is the index value, R is precipitation (inches/month) and M is average monthly temperature (^{o}C) (Oury). The index is increasing in precipitation and decreasing in temperature, thus an increase in index value reflects increased soil moisture availability. This index is attractive for empirical applications due to its continuous properties and relatively benign data requirements. A recent application by Carter and Zhang utilizes the Angstrom Index to analyze the relationship between weather and the variability in China's grain supply. Here, we utilize the index to control for differences in climatic conditions across years.

However, as outlined in the literature review and conceptual framework, time is also hypothesized to have an effect on switchgrass yield response. An empirical model to test whether the shape of the response function changes over time is:

$$(12) \qquad y_k = \beta_0 + \beta_1 x + \beta_2 x^2 + \alpha A + \gamma_1 \frac{1}{t^3} + \gamma_2 tx + \gamma_3 tx^2 + u$$

where x, A, α, β, and the subscript k are as previously defined, t is year of switchgrass growth, u is an error term assumed normally distributed, and the γs are parameters of the time and time by N-rate interaction variables. The time trend variable is specified to exhibit the increasing but diminishing effect on yield during establishment. Functional forms considered for the time trend variable included the log, square root, inverse, inverse squared, and inverse cubed forms. The inverse cubed form was selected because it best modeled the hypothesis maintained by Parrish and Fike that switchgrass stands reach full maturity by the third year of production.

If a dynamic effect exists, we would expect the shape of the response function to change over time. The inclusion of interaction terms between the time and N rate variables allows us to test this empirically. Stated under the null, we test the hypothesis H_0: $\gamma_2 = \gamma_3 = 0$; versus H_a: at least one of the γs is not equal to zero. Rejection of the null supports the notion that yield response to N fertilizer is dynamic, thus requiring a different optimal N rate for each annual production stage. By contrast, failure to reject the hypothesis would imply that a single yield response function averaged over multiple years may be appropriate for determination of economically optimal N rates.

After obtaining empirical estimates for the yield response functions, implications of the estimates on the profitability switchgrass at the farm level are evaluated using Equations 1 through 4. Increased curvature of the response function over time may imply that additional N application also becomes more profitable. When yield response to N is relatively flat, the profit maximizing N rates will be low because the value of yield to be gained from addition N application is insufficient to offset the N fertilizer and application costs. However, as the slope of the response curve increases, the value of yield gain also increases and more easily offsets fertilizer costs. However, should the yield maximum at high N levels also decline over time, these effects may be offsetting and the optimal N rate may remain relatively low.

Data

Five years (2004-2008) of switchgrass yield data were obtained from identical experiments at four locations at the University of Tennessee Milan Research and Education Center at Milan, TN (35°56′ N, 88°43′ W). The locations selected represent the predominant soil types and landscape positions found in West Tennessee. They were: (1) a moderately well drained level upland (WDLU), (2) a well to moderately well drained flood plain (WDFP), (3) a moderate to somewhat poorly drained eroded sloping upland (MDSU), and (4) a poorly drained flood plain (PDFP).

The WDLU and WDFP locations are high-yielding environments well suited for row crop production. The less well drained MDSU and PDFP locations represent intermediate and marginal yield environments, respectively, and have root-restrictive hardpans. They are also characteristic of farmland that typically qualifies for the USDA Conservation Reserve Program. The MDSU landscape, in particular, represents 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.

The experimental design at each location was a randomized complete block with a strip-plot arrangement of treatments and four replications. Stands were established in 2004 with the ‘Alamo’ cultivar. Seeding rates were 2.5, 5.0, 7.5, 10.0, and 12.5 lbs/acre of pure live seed. In 2005, blocks were split in strips for N fertilization. N rates applied were 0, 60, 120, and 180 lbs/acre. Annual N treatments thereafter were identical to 2005 levels. Plots were harvested annually following senescence, with a subsample dried in a forced-air oven to determine percent moisture. Yields were then reported as dry tons per acre.

Table 1 summarizes monthly precipitation, average monthly temperature, and corresponding Angstrom Index values for 2005 to 2008. Rainfall totals were highest in 205, the year after establishment. In 2006 and 2008 rainfall totals were nearly identical, but the monthly distribution was more even in 2006. In 2008, heavy precipitation occurred in April and May but then remained low for the remainder of the growing season. By contrast, 2007 had the lowest overall rainfall with early months being particularly dry. This, combined with extreme high temperatures resulted in near drought conditions for most of the 2007 growing season. The combined effects of low rainfall and high temperatures are reflected by the Angstrom Index values which were higher in 2005 and 2006 as compared to 2007 and 2008.

Table 2 shows average switchgrass yields by year and location. As expected, yields were highest in 2006 stands had reached full maturity and weather was favorable. Notably, the two upland locations MDSU and WDLU far out-yielded the two flood plain locations when weather conditions were favorable in 2006. However, yields were generally equivalent in 2007 and 2008 when weather was less favorable. The low yields for the PDFP location in 2005 and 2006 are partly explained by severe infestations of Broadleaf Signal Grass (*Brachiaria platyphylla* L.) and Crabgrass (*Digitaria sanguinalis*) that canopied the emerging switchgrass early in the season. By contrast, the relatively higher yields for this location in 2007 and 2008 are likely due in part to the poor drainage characteristics that increased moisture availability in dry years.

Results and Discussion

The results and discussion are organized in three sections. We first present empirical findings for the average and dynamic yield response functions. Second, we explore the impact of these findings on producer profitability at the farm level. We then finish with a discussion of the potential implications of these findings from a sustainability perspective.

Yield Response

Estimation results for the average and dynamic switchgrass yield response functions are presented in Table 3. The first set of results reports empirical findings for the average annual response function in Equation 10. Overall, model fit was highly significant for each of the four locations. Corresponding R^2 values were for the well-drained WDFP and WDLU locations and highest for the less-well-drained PDFP and MDSU. Parameter estimates for the linear and quadratic N rate terms had the expected signs and were significant at the $p = 0.01$ level for all but one location suggesting an increasing but diminishing response to N fertilizer. The exception was the PDFP location where only the linear N rate term was found to be statistically significant. The linear response at the PDFP location is likely due location factors such shallow rooting depth and severe weed infestation during establishment. Another contributing factor may be increased N dentrifiction due to the poor drainage characteristics of the soil (Fike et al.). The Angstrom Index to control for annual variations in climatic conditions was also significant at the $p = 0.01$ level for all but the WDFP locations.

The second set of results in Table 3 presents empirical findings for the dynamic switchgrass response function in Equation 12. As compared with results for the average annual response function, addition of the inverse cubed time trend variable and linear time by N-rate interactions greatly improved model fit and R^2 values at all locations. Contrary to the average annual response function, R^2 values are higher for the well-drained WDFP and WDLU locations relative to the PDFP and MDSU locations. Both the inverse cubed time trend and Angstrom Index variables are highly significant for all four locations. The statistical significance of the time by N-rate interaction variables leads us to reject the null hypothesis that the γs are equal. This finding implies that the slope of the response function changes over time, and suggests that switchgrass yield response to N is indeed dynamic. The positive and negative signs of the time by N-rate and time by N-rate squared variables, respectively, imply that the curvature of the response function is increasing with time.

Figures 1 and 2 illustrate predicted switchgrass yields at each of the four locations for the average annual and dynamic yield response functions, respectively, based on an Angstrom Index value of 65 (the average value across months and years). For the average annual response function, yield maximums at all but the PDFP location are predicted to lie between 7.0 and 7.6 dry tons/acre (Figure 1). For the dynamic response function, yield maximums and yield maximizing N rates varied by year (Figure 2). At the WDFP and MDSU locations both yield maximums and yield maximizing N rates increased annually. This finding supports the observation by Lemus et al. that the effect of applied N on switchgrass yield may be beneficial and increasing over time. By contrast, at the WDLU location yield maximums increased but the corresponding yield maximizing N rates decreased over time (Figure 2). For instance, in 2005 the predicted yield maximum occurred at an N rate of 150 lbs/acre, whereas in 2006 the yield maximum occurred at a rate of only 125 lbs/acre. This result for the WDLU location may indicate an outcome similar to that hypothesized by Fike et al. and Parrish et al. where the sustained application of N at high rates reduces yield potential.

Farm-Level Profitability

Table 4 presents the yield maximums, yield-maximizing N rates, profit-maximizing N rates, and net returns to N application for the average annual and dynamic yield response models. Profit-maximizing N rates were determined for a switchgrass biomass price of \$60/ton and an N price of \$0.70/lb. For the average annual response function, differences in the profit-maximizing N rates across locations were minimal due to the relatively flat slope of the response curve and similar yield maximums across locations. Rates ranged from 90 to 115 lbs/acre for all but the PDFP location. The high profit-maximizing N rate for the PDFP location (180 lbs/acre, the maximum rate included in the experiment) is due to the linear shape of the response function. Net return to N application was highest for the WDLU location, and lowest for the PDFP location.

Profit-maximizing N rates based on the dynamic response function were determined for each year individually and by assuming a single identical amount is applied in each year (Table 4). For N applied at identical rates each year, the profit-maximizing rates were lowest for the well drained WDLU and WDFP locations but remained close to 90 lbs/acre. Profit-maximizing rates were 40 to 90 lbs/acre higher than this at the more poorly drained locations. Here, net returns to N application were highest at the MDSU location which contrasts with the average annual response function where the WDLU location had the highest net return.

Because the dynamic function suggests that the slope of the response curve is flat initially but increases with time, gains in net return may be possible by applying N at different rates in each year. When determined by year, profit-maximizing N rates were found to be low initially (<50 lbs/acre) for the well-drained WDLU and WDFP and then increase gradually to over 100 lbs/acre. Profit-maximizing N rates for the more poorly drained locations by contrast were high initially (>100 lbs/acre) and remained so over the four years considered. Results for the WDLU location are particularly interesting. Whereas the yield maximizing N rate was found to decrease for the period 2004-2008, the profit-maximizing N rate increases. This occurs because the increase in slope of the response curve also increases the value of the yield gain from additional N application, thus pushing the profit-maximizing N rate higher despite the decrease in yield-maximizing N rates. Cumulative net returns when N rates were determined by year exceeded net returns for the single N rate at all four locations. The MDSU location again was found to have the highest net return to N application. Assuming the dynamic model provides a better fit, these results suggest the annual response functions overestimate profit-maximizing N rates for the well-drained WDLU and WDFP locations but underestimate the profit-maximizing N rate for the more poorly drained MDSU location.

Implications on Sustainability

The attractiveness of switchgrass as an ethanol feedstock is based, in part, on its ability to produce high yields in marginal soils and minimal management and input requirements. When produced on marginal lands, it is less likely to compete for acres with traditional food crops and therefore may alleviate concerns over the food-versus-fuel debate that surrounds the use of corn for ethanol production. When harvested in the late fall, nutrients in the above ground biomass recycle into the crown root system and remain to support re-growth the following spring. This is thought to lower fertilizer input requirements and thereby reduce the risk of chemical runoff and leaching and reduce the energy and carbon footprint of ethanol production.

Based on the results presented above, a number of observations with respect to switchgrass production from a sustainability perspective are pertinent. Notably, plots at all locations receiving 0 lbs/acre N were found to produce consistent yields without sign of reduced persistence. This suggests that low-input systems of switchgrass production may be sustainable in the long term at locations similar to those included in the experiment. However, many producers may not elect to include switchgrass among their mix of farm enterprises unless it is shown to be profitable. From a commercial perspective, switchgrass producers will likely maximize the net return to fertilizer inputs. As suggested by our results, this rate may lie well above the minimal rates required for sustainability (>100 lbs/acre). Finally, if large portions of bottomland and sloping upland are converted from forage or fallow lands (which do not rely on N fertilization) to switchgrass for bioenergy, overall N application on regional and national levels may increase. Thus, from a regional perspective, switchgrass plantings may increase concerns about N fertilizer use instead of easing them. Important considerations when evaluating the tradeoffs between switchgrass production and alternative bioenergy feedstock sources, important considerations will include the degree to which switchgrass plantings are commercially oriented and to what enterprises it will replace.

Summary and Conclusions

The objectives of this paper were to (i) determine the dynamic properties of switchgrass yield response to N fertilizer, and (ii) evaluate the implications of these properties on the profitability and sustainability of switchgrass at the farm level. Properties of the response function were determined by estimating annual and dynamic quadratic yield response functions. The annual response function controlled for the rate of applied N, location characteristics, and climatic factors. The dynamic response function included the same variables plus time and time by N-rate variables. We rejected the null hypothesis that the time by N-rate interaction variables were equal to zero, thus confirming that the slope of the response curve increases over time.

To determine the implications of the dynamic response properties on farm-level profitability, a multi-period sequential input decision framework was developed. Economically optimal N rates determined using the dynamic response functions were lowest for the two well drained locations, at around 90 lbs/acre. Profit-maximizing rates were 40 to 90 lbs/acre above this rate for the more poorly drained locations. If we assume the dynamic model provides a better fit, results suggest annual response functions overestimate profit-maximizing N rates for the well drained locations but underestimate the profit-maximizing N rates for more poorly drained location. Implications of this dynamic effect on sustainability will depend on the degree to which switchgrass plantings are commercially oriented and on what enterprises it will replace.

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Table 1. Summary of growing season climate data, Milan, TN, 2005-2008

	2005	2006	2007	2008
Monthly Precipitation Totals (inches):				
April	7.55	3.26	3.30	10.22
May	0.59	5.02	2.30	9.39
June	5.08	5.93	4.40	1.52
July	5.32	3.53	2.15	3.10
August	8.09	3.30	1.16	0.72
September	3.77	4.47	7.36	0.47
Total (April-Sept)	30.40	25.51	20.67	25.42
Average Monthly Temperature (°F)				
April	59.1	64.6	55.5	57.4
May	65.2	67.7	71.2	66.6
June	75.1	75.0	76.6	78.0
July	78.6	79.8	77.6	74.7
August	79.9	80.4	86.1	77.3
September	72.7	67.7	73.6	72.4
Average (April-Sept)	71.8	72.5	73.4	71.1
Angstrom Index:				
April	69.3	24.3	34.7	99.8
May	15.0	127.5	13.4	65.0
June	129.0	150.6	20.9	6.9
July	135.1	89.7	9.8	15.8
August	205.5	83.8	3.9	3.3
September	95.8	113.5	39.1	2.6
Average (April-Sept)	108.3	98.2	20.3	32.2

Source: NOAA, Milan, TN weather station.

Table 2. Summary of switchgrass yield data from a field experiment at Milan, TN (dry tons/acre)

Location	Year	N	Mean	Std Dev	Min	Max
MDSU	2005	80	3.97	1.09	1.6	7.7
	2006	80	8.02	3.05	2.4	16.1
	2007	80	3.92	2.06	0.4	9.2
	2008	80	5.63	2.30	0.8	9.8
PDFP	2005	80	3.01	1.19	0.7	6.4
	2006	80	4.71	2.02	1.0	9.3
	2007	80	4.15	1.43	1.4	7.8
	2008	80	5.33	1.66	2.7	10
WDFP	2005	80	4.97	1.36	1.8	8.3
	2006	80	6.96	2.71	0.8	15.8
	2007	80	4.65	1.68	1.3	7.8
	2008	80	6.83	2.34	1.7	11.9
WDLU	2005	80	5.20	0.91	3.5	8.1
	2006	80	10.21	1.82	5.6	14.4
	2007	80	5.18	1.55	2.2	7.6
	2008	80	5.96	1.91	2.7	9.6

Notes: Plots were established in 2004. MDSU = Moderately well drained sloping eroded upland; PDFP = Poorly drained floodplain; WDFP = Well drained floodplain; WDLU = Well drained level upland

Table 3. Regression results for the average and dynamic switchgrass yield response functions, Milan, TN, 2005-2008

Variable	Location							
	WDFP		WDLU		PDFP		MDSU	
Average Annual Response Function								
Intercept	3.731	***	3.163	***	3.504	***	1.466	***
	(0.311)		(0.337)		(0.204)		(0.352)	
Angstrom Index	0.005		0.032	***	-0.013	***	0.021	***
	(0.004)		(0.004)		(0.002)		(0.004)	
Nitrogen rate (lbs/acre)	0.047	***	0.035	***	0.020	***	0.059	***
	(0.006)		(0.007)		(0.004)		(0.007)	
Nitrogen rate squared	-0.00019	***	-0.00013	***	-0.00002		-0.00021	***
	(0.00003)		(0.00003)		(0.00002)		(0.00004)	
Observations	320		319		319		306	
F Value	31.08		41.28		84.99		57.97	
Pr > F	<.0001		<.0001		<.0001		<.0001	
R^2	0.2278		0.2822		0.4474		0.3654	
Dynamic Response Function								
Intercept	1.81	***	1.14	***	2.57	***	-0.54	*
	(0.34)		(0.24)		(0.22)		(0.31)	
Time (inverse cubed)	14.33	***	49.69	***	16.70	***	39.11	***
	(3.57)		(2.51)		(2.35)		(3.18)	
Angstrom Index	0.05	***	0.10	***	0.02	***	0.08	***
	(0.005)		(0.004)		(0.003)		(0.004)	
Nitrogen rate (lbs/acre)	-0.012		-0.020	*	-0.009		0.012	
	(0.016)		(0.011)		(0.010)		(0.014)	
Nitrogen rate × Time	0.017	***	0.016	***	0.008	***	0.014	***
	(0.004)		(0.003)		(0.003)		(0.004)	
Nitrogen rate squared	-0.00002		0.00010		0.00010	*	-0.00008	
	(0.00009)		(0.00006)		(0.00006)		(0.00008)	
Nitrogen rate squared × Time	-0.00005	**	-0.00007	***	-0.00003	**	-0.00004	*
	(0.00002)		(0.00002)		(0.00002)		(0.00002)	
Observations	320		319		319		306	
F Value	41.7		186.99		78.33		117.5	
Pr > F	<.0001		<.0001		<.0001		<.0001	
R2	0.4443		0.7824		0.601		0.7022	

Notes: Standard errors are in parentheses; *** = significant at the 0.01 level; ** = significant at the 0.05 level; * = significant at the 0.10 level; WDFP = Well drained floodplain; WDLU = Well drained level upland; PDFP = Poorly drained floodplain; MDSU = Moderately drained eroded sloping upland.

Table 4. Economic results for the average and dynamic switchgrass yield response functions, Milan, TN, 2005-2008

	Location			
	PDFP	WDLU	WDFP	MDSU
Average annual response function				
Yield-maximizing N rate (lbs/acre)	180	135	120	140
Yield maximum (dry tons)	5.6	7.6	7.0	7.0
Profit-maximizing N rate (lbs/acre)	180	90	95	115
Net return ($/acre)	210	452	412	413
Dynamic response function				
Yield-maximizing N rate (lbs/acre)				
2005	180	150	90	120
2006	180	135	115	130
2007	180	125	130	140
2008	180	125	135	140
Yield maximum (dry tons/acre)				
2005	3.8	2.6	4.1	2.4
2006	5.7	7.9	6.6	7.0
2007	6.6	9.9	8.2	8.9
2008	7.1	11.3	9.7	10.3
Profit-maximizing N rate (lbs/acre) (different rates)				
2005	180	0	45	125
2006	180	80	80	135
2007	175	95	100	140
2008	155	105	115	145
Cumulative net return ($/acre, 2004 USD)	684	1213	1099	1294
Profit-maximizing N rate (lbs/acre/yr) (single rate)	180	85	90	135
Cumulative net return ($/acre, 2004 USD)	682	1,194	1,076	1,291

Notes: Calculations based on an Angstrom Index value of 65 and a 10% discount rate. WDFP = Well drained floodplain; WDLU = Well drained level upland; PDFP = Poorly drained floodplain; MDSU = Moderately drained eroded sloping upland.

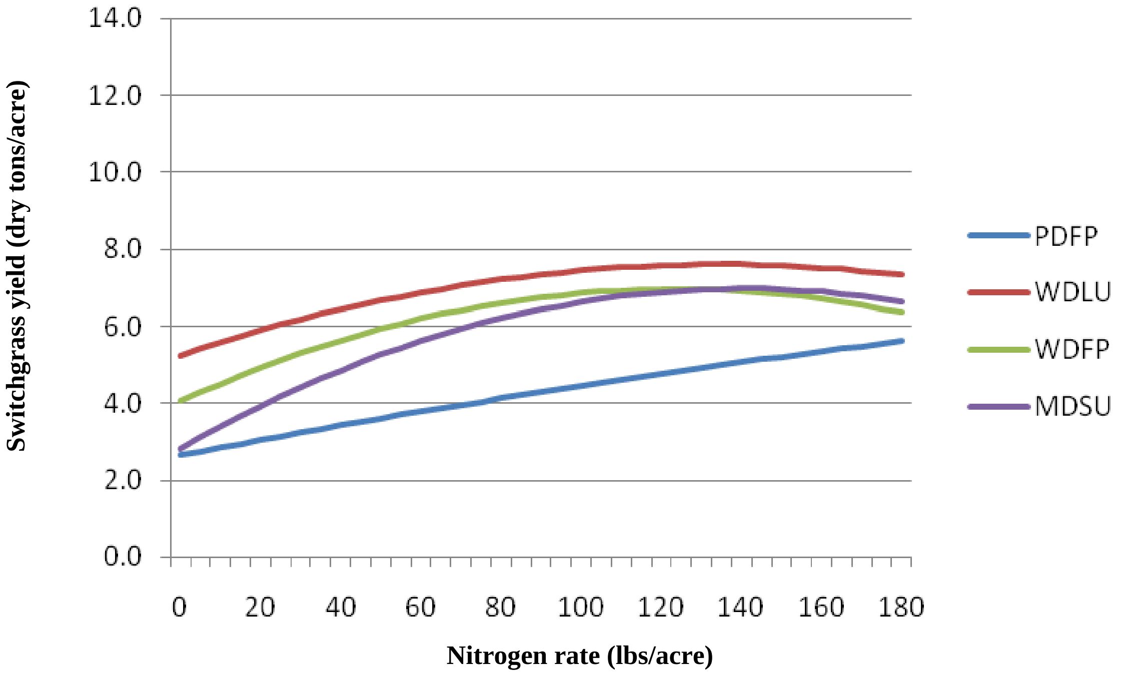

Figure 1. Predicted switchgrass yields for the average response functions, Milan, TN, 2005-2008.

Notes: Predicted yields shown are based on an Angstrom Index value of 65. WDFP = Well drained floodplain; WDLU = Well drained level upland; PDFP = Poorly drained floodplain; MDSU = Moderately drained eroded sloping upland.

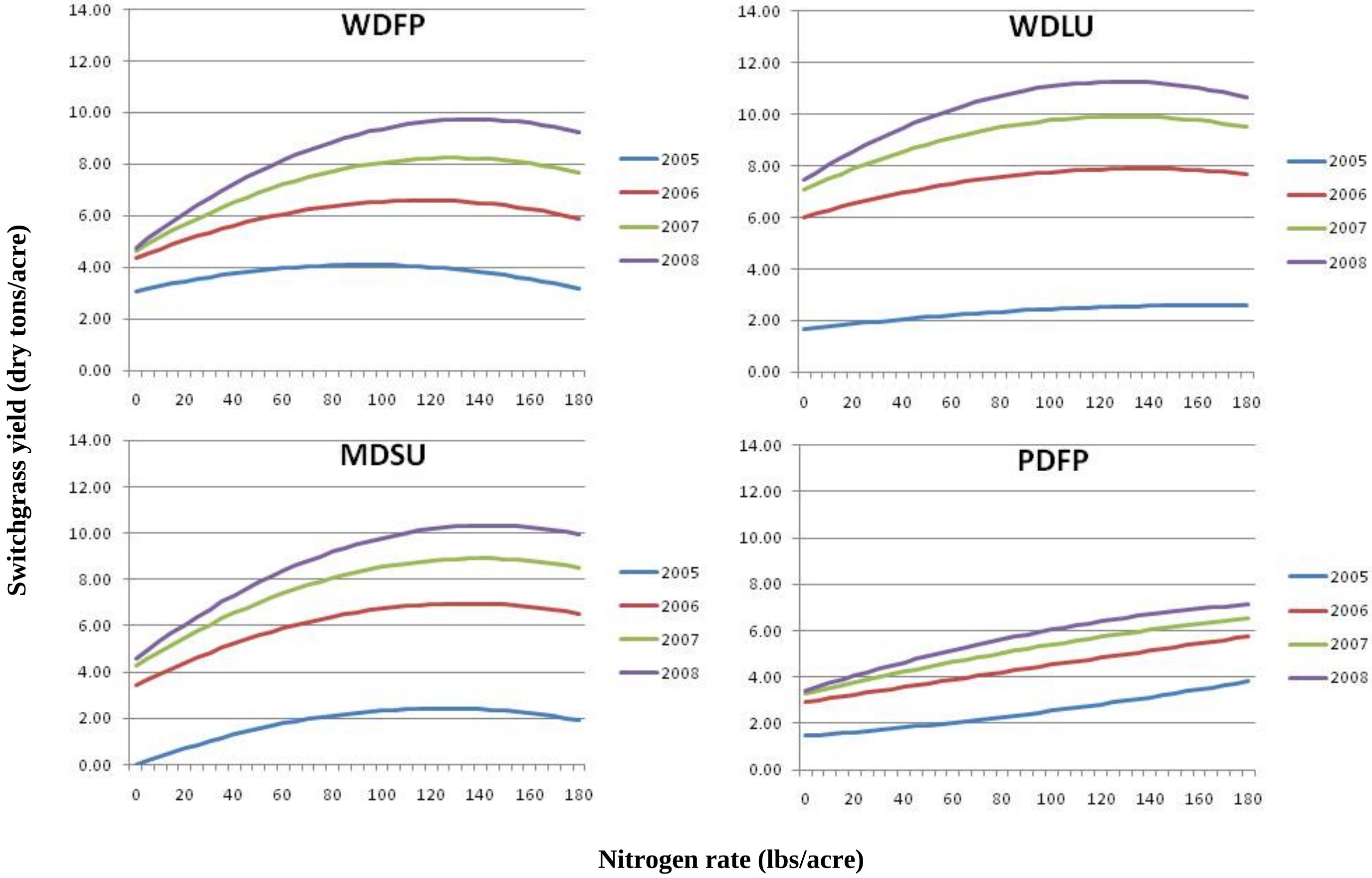

Figure 2. Predicted switchgrass yields for the dynamic response functions, Milan, TN, 2005-2008.

Notes: Predicted yields shown are based on an Angstrom Index value of 65. WDFP = Well drained floodplain; WDLU = Well drained level upland; PDFP = Poorly drained floodplain; MDSU = Moderately drained eroded sloping upland.