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Effects of soil type and landscape on yield and profit maximizing nitrogen rates for switchgrass production

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ARTICLE INFO

Article history:
Received 26 June 2012
Received in revised form
9 November 2012
Accepted 15 November 2012
Available online 23 December 2012

Keywords:
Lignocellulosic biomass
Mixed models
Nitrogen
Profitability
Switchgrass
Tennessee

ABSTRACT

Previous work has found yield-maximizing nitrogen (N) rates in switchgrass production and results have varied widely. Little attention, however, has been given to estimating profit-maximizing N rates. The objectives of this research were to determine the (1) yield- and (2) profit-maximizing N rates for producing switchgrass on four soil types/landscapes in Tennessee. Mixed models were used to perform an analysis of variance on the effects of four N rates on average yield and average net returns for switchgrass grown on the four soil types/landscapes. Data were analyzed from a switchgrass experiment conducted at Milan, Tennessee over a six-year period on: (1) a moderately- to well-drained level upland (WDLU), (2) a moderately- to 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 N rates that maximized average yield were 67, 134, 134, and 200 kg N ha^{-1} for the WDFP, WDLU, MDSU, and PDFP soil types/landscapes, respectively. The profit-maximizing N rate was estimated by soil type/landscape using three prices of switchgrass and three prices of N. Results demonstrated that yield- and profit-maximizing N rates can be different, and the yield- and profit-maximizing N rates across different across the soil types/landscapes. The profit-maximizing N rate was sensitive to the price of N and the price of switchgrass across all soil types/landscapes, but sensitivity to price changes were not equal for all soil types/landscapes.

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1. Introduction

Concerns about the impact of the corn ethanol industry on food prices [1–3], net energy requirements [4], environmental damages such as soil erosion and water contamination by nutrients and chemicals [5–7], and the loss of biocontrol services that regulate agroecosystems [8] have spurred research in lignocellulosic biomass (LCB). The Energy

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0961-9534/$ – see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.biombioe.2012.11.004

Independence and Security Act of 2007 mandates at least 6.06×10^{10} L (16 billion gallons) of LCB biofuels of the 1.36×10^{11} L total required by the Act [9]. If the mandated LCB biofuels benchmark is met, up to 16.9 million ha (about 10% of the U.S. agricultural land base) could be used for LCB production depending on market conditions [10]. The majority of this land is predicted to come from land considered to be marginal or poor for the production of row crops [11,12] or land that is enrolled in the Conservation Reserve Program [6,13]. In the southern United States, LCB crops may hold a competitive advantage over corn ethanol because the growing seasons are longer and historical corn yields are lower compared to other regions of the United States [11,14–16].

The southern United States has the potential to produce LCB from several sources such as agricultural residues, forest residues, urban wood waste, mill waste, and dedicated energy crops [14]. English et al. [14] found that dedicated energy crops have a greater potential to be an economically viable LCB source in this region than residue and waste products. The dedicated energy crops most commonly analyzed for the southern United States include switchgrass (*Panicum Virgatum* L.) [6,14,17–19], poplar (*Populus* spp.) [6,17], and willow (*Salix* ssp.) [6,17]. Miscanthus (*M.* x *giganteus*) has also shown promise in the United States [18,19], but not likely in the southern states. The cost of producing switchgrass is lower than the costs of producing poplar and willow [6,17], giving switchgrass an economic advantage. Furthermore, many producers in the southern United States have expressed interest in growing switchgrass if it is economically viable [20].

Switchgrass is a perennial, warm-season grass widely recognized for its potential as an LCB crop in North America [21,22]. Switchgrass can produce high yields on land considered to be marginal for crop production while requiring low management intensity [23]. Additionally, switchgrass can improve soil quality by sequestering carbon [24], and when harvested once in the fall following senescence, nutrients move from the above-ground biomass into the root system, minimizing the need for their replacement and reducing the potential for nutrient water contamination [25]. Although switchgrass production provides many agronomic benefits, several challenges exist to making LCB switchgrass production economically viable including issues regarding input use, harvesting, transportation, and storage [26,27]. For example, Larson et al. [26] calculated harvesting, transportation, and storage cost for three logistic methods of acquiring switchgrass for a refinery, and Mooney et al. [27] estimated the net returns to harvesting and storing switchgrass while considering dry matter loss. Both of these studies provide important insight into improving the economic viability of switchgrass, but indicate more research is needed in these areas. Furthermore, a meta-analysis of switchgrass yields found that an annual application of nitrogen (N) is required to produce yields large enough to make switchgrass production economically feasible [19]; however, little is known about the profit-maximizing N rate for switchgrass production.

Determining the N rate that maximizes producers' profits is vital to increasing the economic feasibility of switchgrass production. Researchers, however, mostly estimate yield-maximizing N rates for switchgrass, and the results have varied depending on several spatial and temporal factors such as soil types and weather [23]. For instance, Muir et al. [28] estimated the yield-maximizing N rate to be 168 kg N ha^{-1} for 'Alamo' switchgrass produced in Texas over a seven-year time frame. Vogel et al. [29] modeled yield response to N for switchgrass grown in Iowa and Nebraska for two years, and found a yield-maximizing N rate of 120 kg N ha^{-1}. Lemus et al. [30] tested mean yield response to various N rates from a five-year, large-field experiment for established switchgrass in Iowa, and concluded that the yield-maximizing N rate was 112 kg N ha^{-1}. For three years of data in Oklahoma, Thomason et al. [31] found 448 kg N ha^{-1} achieved the highest annual switchgrass yield when harvested multiple times. More recent analyzes of two years of switchgrass yields in Oklahoma found yield-maximizing N rates ranging from 135 to 180 kg N ha^{-1} depending on the number of harvests [32,33]. Mulkey et al. [34] compared mean yields of switchgrass planted on land enrolled in the Conservation Reserve Program in South Dakota for five years, and discovered the yield-maximizing N rate for this marginal land to be 56 kg N ha^{-1}. Mooney et al. [16] found yield-maximizing N rates for 'Alamo' switchgrass grown in Tennessee over three years to range from 67 to 200 kg N ha^{-1} depending on the soil type/landscape. The sensitivity of switchgrass yield response to N on the different soil types/landscapes under the same climate conditions found by Mooney et al. [16] was an important contribution to the literature.

It is clear switchgrass responds positively to N fertilizer, and applying N is vital to the economic viability of switchgrass production for LCB. In contrast, the economic importance of N fertilizer in the production of poplar and willow for LCB is unclear [35]. Although a few studies have found poplar to positively respond to N fertilization rates ranging from 50 kg N ha^{-1} to 224 kg N ha^{-1} [36,37], and Somerville et al. [38] found lower N rates between 0 and 50 kg N ha^{-1}. Recently, however, Balasus et al. [39] found no evidence that N fertilization is necessary in producing poplar for LCB. Several researchers found willow yield to positively respond to N fertilization rates ranging from 75 kg N ha^{-1} to 336 kg N ha^{-1} [36,39–41], but Balasus et al. [35] also found willow unresponsive to N fertilizer. Notwithstanding a need for further research on optimal N fertilization rates for poplar and willow, the lower cost of producing switchgrass [6,17], combined with its clear response to N fertilization, suggests that determining profit-maximizing switchgrass N rates is important for the economic viability of dedicated energy crops in the southern United States.

A few papers have gone beyond determining the yield-maximizing N rate by calculating the N rate that maximizes producers' profit. The profit-maximizing N rate can be different from the yield-maximizing N rate depending on the prices of switchgrass and N. For example, if the revenue gains received from yield increases due to additional N at the yield-maximizing N rate are less than the cost of the additional N, the profit-maximizing N rate will be less than the yield-maximizing N rate. Haque et al. [42] found the profit-maximizing N rate for switchgrass grown in Oklahoma to be 65 kg N ha^{-1}. Aravindhakshan et al. [43] found 69 kg N ha^{-1} to be the economically optimal N rate for established switchgrass in Oklahoma. A limitation of their research is that only three years of data from one location were analyzed to find the profit-maximizing N rates. More research is needed to determine how profit-maximizing N rates vary on different soil types and landscapes over a longer time period, particularly in the southern United States where switchgrass is likely to be grown [11,14–16]. The impact of soil type on switchgrass yield has been discounted in previous studies [44], and more research is needed to better understand the impact of soil quality on the economic feasibility of switchgrass production [45]. Shield et al. [46] recently demonstrated that switchgrass may be unable to produce financially viable yields on sites that have low productivity.

The objectives of this research were to determine the yield- and profit-maximizing N rates for switchgrass production on four soil types/landscapes in Tennessee. An analysis of variance (ANOVA) approach was implemented to find the fixed effects of four N rates on average yield by soil type/landscape, and a paired comparison test was used to determine the yield-maximizing N rate by soil type/landscape. An ANOVA was also performed to find the fixed effects of four N rates on average net returns by soil type/landscape, and a paired comparisons test was used to determine the N rate that maximizes average net returns by soil types/landscapes. A sensitivity analysis with a broad range of switchgrass and nitrogen prices was implemented to show how profit-maximizing N-rate recommendations vary by the price of switchgrass and the price of N across the soil types/landscapes. The dataset used for the analysis includes a longer time period and more diverse soil types and landscapes than currently found in the literature. The results from this research provide useful insights into how switchgrass responds to N on different soil types/landscapes, and can be used to improve N-rate recommendations to maximize producers' average net returns.

2. Theory

Partial budgeting was used under the expected profit-maximization framework to analyze the profitability of applying each N rate on the four soil types/landscapes. The switchgrass producer was presumed to be risk-neutral with the objective of maximizing expected net returns [47]. The producer's objective function can be expressed mathematically as

$$\max_{x_j} E(NR_j) = pE\left(y_j\right) - rx_j - h\left(y_j\right) \quad (1)$$

where $E(NR_j)$ is the producer's expected (average) net returns in \$ ha^{-1} for the jth ($j = 1,2,\ldots,J$) N treatment in kg N ha^{-1}; p is the price of switchgrass in \$ Mg^{-1}; $E(y_j)$ is the expected (average) switchgrass yield in Mg ha^{-1} for N treatment j; r is the cost of N in \$ kg^{-1}; $h(y_j)$ is the harvest cost in Mg ha^{-1}; and x_j is the quantity of N applied in kg ha^{-1} for the jth N treatment. Other costs that are normally included in a production budget such as seeding rate, herbicide, machinery, establishment, and labor are assumed to be equal across the soil types/landscapes and N rates since these costs vary little with yield. Harvest costs, however, are a function of yield. Harvest costs in the literature includes: mowing, raking, baling and staging [16,48]. Mowing and raking costs are measured as ha^{-1} costs while baling and staging costs vary with yield [16,48]. Staging cost is the cost of collecting and loading bales from the spot of the field where they were dumped by the baler. This cost includes the costs of transporting, offloading and stacking the bales at a storage facility. Even though mowing and raking do not vary by yield, the costs are included in our partial budget to fully represent harvest costs.

Expected net returns are maximized when the marginal value product from the N rate is equal to the marginal factor cost of the N rate [47]. That is, a producer increases the N rate until the revenue gained from yield increases equals the cost of the added N. Therefore, the N rate that maximizes expected net returns may or may not be the same rate that maximizes expected yield. Haque et al. [42] and Aravindhakshan et al. [43] found the profit-maximizing and yield-maximizing N rates to be the same, but only because the response function they selected to use imposed a corner solution.

3. Data

Six years (2005–2010) of switchgrass yield data were obtained from identical experiments at four sites at the University of Tennessee Milan Research and Education Center at Milan, TN (35°56′ N, 88°43′ W). The four soil types/landscapes included were: (1) a 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 soil type/landscape was primarily Grenada silt loam (fine-silty, mixed, active, thermic Oxyaquic Fraglossudalfs), and the soil type for WDFP was Vicksburg silt loam (coarse-silty, mixed, active, acid, thermic Typic Udifluvents) and Collins silt loam (coarse-silty, mixed, active, acid, thermic Aquic Udifluenvents). These soil types/landscapes are well suited for row crop production in Tennessee. The MDSU and PDFP soil types/landscapes represent marginal soil types/landscapes that likely qualify for the USDA Conservation Reserve Program. The MDSU soil type/landscape was moderately eroded Grenada silt loam (fine-silty, mixed, active, thermic Oxyaquic Fraglossudalfs) with a 6% slope, and the PDFP soil type/landscape was mostly Falaya silt loam (coarse-silty, mixed, active, acid, thermic Aeric Fluvaquents) and Waverly silt loam (coarse-silty, mixed, active, acid, thermic Fluvaquentic Endoaquepts). The MDSU soil type/landscape represents the majority of the farmland in West Tennessee and was thought to be a likely soil type/landscape to grow switchgrass [16]. Previous analysis on switchgrass yields from these same soil types/landscapes from 2004 to 2006 shows clear spatial differences among the soil types/landscapes [16].

The experimental design for each soil type/landscape was a randomized complete block with a strip-plot arrangement of treatments and four replications. Stands were establishment in 2004 with the 'Alamo' cultivar, and no N was applied in the establishment year. In 2005, the blocks were split in strips for N fertilization at 0, 67, 134 and 200 kg N ha^{-1}. These N rates were applied annually through 2010. Ammonium nitrate was the N source. Soil samples tests were taken before establishment found medium quantities of K for two of the soil types/

landscapes and low levels of K were found on the PDFP and MDSU soil types/landscapes. Medium to high quantities of P were found for all the soil types/landscapes. Even though switchgrass produced as bioenergy feedstock does not require much P and K [16], 89.7 kg P_2O_5 ha^{-1} and 89.7 kg K_2O ha^{-1} were applied to all the soil types/landscapes. Plots were 29.2 by 4.6 m and were harvested annually following senescence, with a subsample dried in a forced-air oven to determine percent moisture. Yields were then reported as dry Mg ha^{-1}.

Table 1 summarizes monthly precipitation and average monthly temperature at Milan, TN [49]. All four soil types/landscapes were located at the University of Tennessee Milan Research and Education Center at Milan, TN, so weather in a given year was the same across the soil types/locations. In 2006 and 2008 rainfall totals were nearly identical, but the distribution of rain over the months was different. In 2008, heavy precipitation occurred in April and May, but was low for the remainder of the growing season. By contrast, 2007 had the lowest overall rainfall with early months being particularly dry. This low rainfall, combined with extremely high temperatures resulted in near drought conditions for most of the 2007 growing season. In 2010, growing conditions were good since both rainfall and average temperature were the highest of all the years.

We used previous switchgrass research and published data to develop switchgrass and N prices for use in evaluating expected net returns. Epplin et al. [50] estimated the breakeven price for switchgrass production at \$56 Mg^{-1}, and Mooney et al. [16] calculated the breakeven price in Tennessee to range between \$53 and \$79 Mg^{-1}. More recently, Griffith et al. [48] estimated breakeven prices for switchgrass production ranging from \$52 to \$63 Mg^{-1}. Following the breakeven prices found in the literature, three switchgrass prices of \$50 Mg^{-1}, \$70 Mg^{-1}, and \$90 Mg^{-1} were used in our partial budgets. The 2005–2010 average price of N from ammonium nitrate was \$1.30 kg^{-1} [51]. We used three N prices of \$0.70 kg^{-1}, \$1.30 kg^{-1}, and \$1.90 kg^{-1}. Harvest costs from Griffith et al.'s [48] switchgrass budgets were used. The price of mowing was \$24.98 ha^{-1}, the price of raking was \$9.59 ha^{-1}, the price of baling (for a 681 kg bale) was \$14.64 $bale^{-1}$, and the price of staging was \$4.50 $bale^{-1}$.

4. ANOVA models

A mixed model was used to perform an ANOVA on the effects of each N rate on average yield. A random effect was included for year variability such as stochastic weather events and disease. The following model was estimated separately for each of the four soil types/landscapes

$$y_{tj} = \gamma_0 + \sum_{j=1}^{J-1} \gamma_j I_j + \upsilon_t + \varepsilon_{tj}, \quad (2)$$

where y_{tj} is the yield in Mg ha^{-1} at time t for the jth N treatment (kg ha^{-1}); I_j is an indicator variable for the jth treatment ($j = 1,2,\ldots,J$); γ_0 is the intercept coefficient, γ_j is the coefficient for N treatment j; $\upsilon_t \sim N(0, \sigma_\upsilon^2)$is the year random effect; and $\varepsilon_t \sim N(0, \sigma_\varepsilon^2)$is a random error term. Independence was assumed across the two stochastic components. One of the j treatments was drop to avoid multicollinearity issues, but was captured by the intercept coefficient. The null hypothesis was average yields are not different across N treatments. We used the MIXED procedure in SAS [52] to estimate this model, and the PDIFF function of LSMEANS was used to compare means. Significance was determined at $p \leq 0.05$.

We used an ANOVA approach to analyze yield changes at the different N rates primarily because this is the approach used in most of the literature [16,30–34]. The ANOVA approach allows more direct comparisons between yield response to N in Tennessee and in other areas across the United States. An alternative to this approach is to estimate yield response functions. Estimating yield response functions is left to future research, because numerous functional forms can be investigated to determine which one fits the data best for each soil type/landscape. The analysis in this article is meant to be more straightforward in the evaluation of

Table 1 – Summary of growing season precipitation and temperature data, Milan, TN, 2005–2010.

Months	2005	2006	2007	2008	2009	2010	30-Year average
Monthly Precipitation Totals (cm)							
April	19.18	8.28	8.38	25.96	8.13	15.24	12.28
May	1.50	12.75	5.84	23.85	22.86	53.59	16.12
June	12.90	15.06	11.18	3.86	5.59	8.13	11.00
July	13.51	8.97	5.46	7.87	20.07	14.99	11.18
August	20.55	8.38	2.95	1.83	5.59	5.08	7.21
September	9.58	11.35	18.69	1.19	11.94	1.02	10.86
Total (April–Sept)	77.22	64.80	52.50	64.57	74.52	97.89	67.68
Average Monthly Temperature (°C)							
April	15.06	18.11	13.06	14.11	14.94	17.06	14.84
May	18.44	19.83	21.78	19.22	19.83	21.78	19.73
June	23.94	23.89	24.78	25.56	26.00	27.56	24.07
July	25.89	26.56	25.33	23.72	24.61	27.61	26.00
August	26.61	26.89	30.06	25.17	24.61	27.83	25.45
September	22.61	19.83	23.11	22.44	22.44	23.11	21.35
Average (April–Sept)	22.11	22.50	23.00	21.72	22.06	24.17	21.96

Source: NOAA, Milan, TN weather station.

swithcgrass yield response to N fertilization. Not only does the ANOVA approach provide more direct comparisons with most of the literature, but it provides insight into the functional forms for evaluation in future research.

Equation (1) was used to calculate average net returns for each N rate, and a similar mixed model was used to estimate the fixed effects of N on average net returns for each soil type/landscape. A random effect was included for year variability. The following model was estimated separately for each of the four soil types/landscapes

$$NR_{tj} = \beta_0 + \sum_{j=1}^{J-1} \beta_j I_j + \upsilon_t + e_{tj},$$

where NR_{tj} is the net returns in \$ ha^{-1} at time t for the jth N rate (kg ha^{-1}); I_j is an indicator variable for the jth treatment ($j = 1,2,\ldots,J$); β_0 is the intercept coefficient, β_j is the coefficient for N treatment j; $\upsilon_t \sim N(0, \sigma_\upsilon^2)$is the year random effect; and $e_t \sim N(0, \sigma_e^2)$ is a random error term. Independence was assumed across the two stochastic components. One of the j treatments was drop to avoid multicollinearity issues, but was captured by the intercept coefficient. The null hypothesis was that average net returns are not different across the N treatments. We used the MIXED procedure in SAS [51] to estimate this model, and the PDIFF function of LSMEANS was used to compare means. Significance was determined at $p \leq 0.05$.

5. Results and discussion

5.1. *Yield*

The results for the yield mixed model are presented in Table 2. For each soil type/landscape, within year average yields are shown by N rate, and the six-year average yields were compared to determine differences across N rates. Yields across years on each soil types/landscapes show variability likely explained by yearly rainfall. Milan, Tennessee received timely rains in 2006 resulting in abnormally high yields on the WDLU and MDSU soil types/landscapes; however, the timely rains had a smaller effect on switchgrass yields grown on the WDFP and PDFP soil types/landscapes. Additionally, the drought conditions in 2007 decreased yields differently across soil types/landscapes. These varying weather events partly explain why the yield-maximizing N rate varies across years. When comparing the average yields across N rates, the random effect variable in equation (2) captures these and other stochastic components across years.

For the WDFP soil type/landscape, average yields were 9.74, 15.97, 16.25, and 15.58 Mg ha^{-1} when 0, 67, 134, and 200 kg N ha^{-1} were applied, respectively. Compared to the control N treatment, average yields for switchgrass increased 64%, 67%, and 60% when 67, 134, and 200 kg N ha^{-1} were applied, respectively. No statistical differences were found in average yields across the 67, 134, and 200 kg N ha^{-1} treatments. Thus, average yield was maximized at the rate of 67 kg N ha^{-1} since applying additional N did not statistically increase yield. This yield-maximizing rate was similar to what Mulkey et al. [34] found for soils in South Dakota that were previously in Conservation Reserve Program, and to what Haque et al. [42] and Aravindhakshan et al. [43] found in Oklahoma.

For the WDLU soil type/landscape, the average yields for switchgrass were 12.04, 16.61, 18.02, and 17.99 Mg ha^{-1} when 0, 67, 134, and 200 kg N ha^{-1} were applied, respectively. Relative to the control N treatment, average yield increased by 38% with the application of 67 kg N ha^{-1}, and by an additional 9% when the N rate increased from 67 to 134 kg N ha^{-1}. There was no statistical difference in average yield between the 134 kg N ha^{-1} treatment and the 200 kg N ha^{-1} treatment. Thus, the average yield-maximizing N rate for the WDLU soil

Table 2 – Switchgrass yields (Mg ha^{-1}) by year and nitrogen rate (kg ha^{-1}) for each soil type/landscape.

Soil Type/ Landscape	N (kg ha^{-1})	Yields (Mg ha^{-1})						
		2005	2006	2007	2008	2009	2010	Average yield
WDFP	0	10.09	12.72	6.33	9.58	9.84	9.87	9.74[a]
	67	13.54	20.10	12.10	17.98	17.60	14.52	15.97[b]
	134	12.73	19.75	13.26	19.88	17.54	14.31	16.25[b]
	200	12.74	16.24	14.31	20.03	16.71	13.45	15.58[b]
WDLU	0	12.89	21.34	7.76	8.82	10.33	11.09	12.04[a]
	67	12.49	25.74	14.21	14.59	16.94	15.71	16.61[b]
	134	12.78	26.39	16.00	18.69	19.49	14.89	18.02[c]
	200	13.23	27.41	13.21	17.17	19.91	17.00	17.99[c]
MDSU	0	7.90	10.42	3.68	5.48	7.99	8.76	7.38[a]
	67	10.11	20.90	8.39	14.66	19.28	17.36	15.11[b]
	134	10.91	25.52	13.34	17.87	20.11	20.00	17.95[c]
	200	10.34	22.45	12.76	17.46	18.79	21.03	17.12[c]
PDFP	0	4.18	7.89	5.83	8.60	8.39	11.73	7.77[a]
	67	6.60	9.87	9.74	12.97	14.80	17.94	12.00[b]
	134	8.82	12.27	12.16	14.06	16.04	19.79	13.86[c]
	200	10.17	16.48	13.26	17.29	18.11	21.20	16.08[d]

Notes: Paired mean tests are performed for each N rate at each soil type/landscape. If the letter is the same across N rates at one location for average yield, the yields are not different at the 0.05 level. WDLU is a moderately-to well-drained level upland; WDFP is a moderately- to well-drained flood plain; MDSU is a moderate- to somewhat poorly-drained eroded sloping upland; and PDFP is a poorly-drained flood plain.

type/landscape was 134 kg N ha^{-1}. This yield-maximizing N rate was higher than the WDFP result, but was similar to the yield-maximizing N rates found by Muir et al. [28] in Texas, Lemus et al. [30] in Iowa, and Vogel et al. [29] in Iowa and Nebraska.

The average yields for switchgrass grown on the MDSU soil types were 7.38, 15.11, 17.95, and 17.12 Mg ha^{-1} when 0, 67, 134, and 200 kg N ha^{-1} were applied, respectively. In going from a zero N rate to 67 kg N ha^{-1}, average switchgrass yield increased 104%, which is a greater yield response to N than for the WDFP and WDLU soil types/landscapes. Average yield increased an additional 19% when the N rate increased from 67 to 134 kg N ha^{-1}, but did not increase further with the 200 kg N ha^{-1} treatment. Average yield was maximized at the 134 kg N ha^{-1} since applying more N did not increase average yield. Overall, the average yield response to N for the MDSU soil type/landscape was similar to the WDLU results.

For the PDFP soil type/landscape, the average yields for switchgrass were 7.77, 12.00, 13.86, and 16.08 Mg ha^{-1} when 0, 67, 134, and 200 kg N ha^{-1} were applied, respectively. Average switchgrass yield increased at every incremental level of N applied in this experiment. Thus, the average yield-maximizing N rate for the PDFP soil type/landscape was 200 kg N ha^{-1}. This yield-maximizing rate was higher than the other soil types/landscapes in this experiment and other experiments found in the literature that harvest switchgrass once a year. The characteristics of this soil type/landscape likely caused a longer establishment period and peak yields had not yet been reached by 2010. Ever and Parson [53] have also shown that soil type and moisture level can influence establishment of switchgrass. Also, N losses due to the poorly-drained nature of the soil might explain the observed yield response at high N rates.

5.2. *Net returns*

Table 3 presents net returns when the price of switchgrass is \$50 Mg^{-1}, \$70 Mg^{-1}, and \$90 Mg^{-1} and the price of N is \$0.70 kg^{-1}. For the WDFP soil type/landscape, the profit-maximizing N rate was 67 kg N ha^{-1} for all the prices of switchgrass, which matches the yield-maximizing N rate for this soil type/landscape and the literature [42,43]. For the WDLU soil type/landscape, the profit-maximizing N rate was 67 kg N ha^{-1} when the price of switchgrass is \$50 Mg^{-1} and \$70 Mg^{-1}; however, when the price of switchgrass is \$90 Mg^{-1}, the profit-maximizing N rate is 134 kg N ha^{-1}. At the two lower prices of switchgrass, the marginal value product of the yield gain was less than the marginal factor cost of the additional N so the profit-maximizing N rate was less than the yield-maximizing N rate. However, at \$90 Mg^{-1}, the marginal value product was greater than the marginal factor cost of the additional N so the profit-maximizing N rate and yield-maximizing N rate were equal. The profit-maximizing N rate for the MDSU soil type/landscape was 134 kg N ha^{-1} for all the switchgrass prices. This is the same as the yield-maximizing N rate for this soil type/landscape. Lastly, for the PDFP soil type/landscape, the profit-maximizing N rate was 67 kg N ha^{-1} when switchgrass was \$50 Mg ha^{-1}, but when the price is \$70 Mg^{-1} and \$90 Mg^{-1}, the profit-maximizing N rate was 200 kg N ha^{-1}. The later N rate is the same as the yield-maximizing N rate for this soil type/landscape.

Table 4 shows the net returns for the prices of switchgrass and a price of N of \$1.30 kg^{-1}. For the WDFP soil type/landscape, the profit-maximizing N rate was 67 kg N ha^{-1} for all the prices of switchgrass. The WDFP soil type/landscape was not sensitivity to the higher N price since the profit-maximizing N rate was equal to the yield-maximizing N

Table 3 – Switchgrass net returns (\$ ha^{-1}) by nitrogen rate (kg ha^{-1}) and soil type/landscape for three switchgrass prices and a nitrogen price of \$0.70 kg^{-1}.

Soil Type/ Landscape	N (kg ha^{-1})	Net returns (\$ ha^{-1})		
		Switchgrass price \$50 Mg^{-1}	Switchgrass price \$70 Mg^{-1}	Switchgrass price \$90 Mg^{-1}
WDFP	0	179^{a}	373^{a}	568^{a}
	67	268^{c}	587^{c}	907^{c}
	134	226^{b}	551^{c}	877^{c}
	200	165^{a}	476^{b}	788^{b}
WDLU	0	229^{a}	470^{a}	711^{a}
	67	282^{c}	614^{c}	947^{b}
	134	266^{b}	626^{c}	987^{c}
	200	218^{a}	578^{b}	937^{b}
MDSU	0	127^{a}	275^{a}	422^{a}
	67	249^{c}	551^{b}	853^{b}
	134	264^{c}	623^{c}	982^{c}
	200	199^{b}	541^{b}	884^{b}
PDFP	0	136^{a}	291^{a}	446^{a}
	67	181^{b}	421^{b}	661^{b}
	134	175^{b}	452^{c}	729^{c}
	200	176^{b}	498^{d}	820^{d}

Notes: Paired mean tests are performed for each N rate at each soil type/landscape. If the letter is the same across N rates at one location for average yield, the yields are not different at the 0.05 level. WDLU is a moderately-to well-drained level upland; WDFP is a moderately- to well-drained flood plain; MDSU is a moderate- to somewhat poorly-drained eroded sloping upland; and PDFP is a poorly-drained flood plain.

Table 4 – Switchgrass net returns (\$ ha^{-1}) by nitrogen rate (kg ha^{-1}) and soil type/landscape for three switchgrass prices and a nitrogen price of \$1.30 kg^{-1}.

Soil Type/ Landscape	N (kg ha^{-1})	Net returns (\$ ha^{-1})		
		Switchgrass price \$50 Mg^{-1}	Switchgrass price \$70 Mg^{-1}	Switchgrass price \$90 Mg^{-1}
WDFP	0	179^{c}	373^{a}	568^{a}
	67	228^{d}	547^{c}	867^{d}
	134	146^{b}	471^{b}	796^{c}
	200	44^{a}	356^{a}	667^{b}
WDLU	0	229^{c}	470^{a}	711^{a}
	67	241^{c}	574^{c}	906^{c}
	134	185^{b}	546^{b}	906^{c}
	200	97^{a}	457^{a}	816^{b}
MDSU	0	127^{b}	275^{a}	422^{a}
	67	208^{d}	511^{c}	813^{c}
	134	184^{c}	543^{c}	901^{d}
	200	78^{a}	420^{b}	763^{b}
PDFP	0	136^{c}	291^{a}	446^{a}
	67	141^{c}	381^{b}	621^{b}
	134	94^{b}	371^{b}	649^{b}
	200	55^{a}	377^{b}	699^{c}

Notes: Paired mean tests are performed for each N rate at each soil type/landscape. If the letter is the same across N rates at one location for average yield, the yields are not different at the 0.05 level. WDLU is a moderately-to well-drained level upland; WDFP is a moderately- to well-drained flood plain; MDSU is a moderate- to somewhat poorly-drained eroded sloping upland; and PDFP is a poorly-drained flood plain.

rate. For the WDLU soil type/landscape, the profit-maximizing N rate was 67 kg N ha^{-1} for all switchgrass prices. This N rate is lower than the yield-maximizing N. The higher N price results in the marginal value product of the yield gain being less than the marginal factor cost of the additional N needed to maximize yield. For the MDSU soil type/landscape, the profit-maximizing N rate was 67 kg N ha^{-1} when the price of switchgrass was \$50 Mg^{-1} and \$70 Mg^{-1}, but at \$90 Mg^{-1}, the profit-maximizing N rate was 134 kg N ha^{-1}. The profit-maximizing N rate for the MDSU soil type/landscape was sensitivity to the higher N price. The profit-maximizing N rate for the PDFP soil type/landscape was 0 kg N ha^{-1}, 67 kg N ha^{-1}, and 200 kg N ha^{-1} when the price of switchgrass was \$50 Mg^{-1}, \$70 Mg^{-1}, and \$90 Mg^{-1}, respectively. The profit-maximizing N rate was sensitive to the higher N price for this soil type/ landscape.

Table 5 – Switchgrass net returns (\$ ha^{-1}) by nitrogen rate (kg ha^{-1}) and soil type/landscape for three switchgrass prices and a nitrogen price of \$1.90 kg^{-1}.

Soil Type/ Landscape	N (kg ha^{-1})	Net returns (\$ ha^{-1})		
		Switchgrass price \$50 Mg^{-1}	Switchgrass price \$70 Mg^{-1}	Switchgrass price \$90 Mg^{-1}
WDFP	0	179^{c}	373^{b}	568^{a}
	67	187^{c}	507^{c}	826^{c}
	134	66^{b}	391^{b}	715^{b}
	200	-77^{a}	235^{a}	546^{a}
WDLU	0	229^{d}	470^{b}	711^{b}
	67	201^{c}	534^{c}	866^{c}
	134	104^{b}	465^{b}	825^{c}
	200	-24^{a}	336^{a}	695^{a}
MDSU	0	127^{c}	275^{a}	422^{a}
	67	168^{d}	471^{b}	773^{c}
	134	103^{b}	462^{b}	821^{c}
	200	-43^{a}	299^{a}	642^{b}
PDFP	0	136^{d}	291^{b}	446^{a}
	67	100^{c}	340^{c}	580^{b}
	134	13^{b}	291^{b}	568^{b}
	200	-66^{a}	256^{a}	578^{b}

Notes: Paired mean tests are performed for each N rate at each soil type/landscape. If the letter is the same across N rates at one location for average yield, the yields are not different at the 0.05 level. WDLU is a moderately-to well-drained level upland; WDFP is a moderately- to well-drained flood plain; MDSU is a moderate- to somewhat poorly-drained eroded sloping upland; and PDFP is a poorly-drained flood plain.

Results in Table 5 shows the net returns for three switchgrass prices when the price of N was \$1.90 kg^{-1}. For the WDFP soil type/landscape, the profit-maximizing N rate was 0 kg N ha^{-1} when the price of switchgrass was \$50 Mg^{-1}, but at the two higher prices of switchgrass, the profit-maximizing N rate was 67 kg N ha^{-1}. The profit-maximizing N rate for this soil type/landscape was not sensitive at the two lower N prices, but at the lowest price of switchgrass and highest price of N, the profit-maximizing N rate decreased. Similarly, the profit-maximizing N rate for the WDLU soil type/landscape was 0 kg N ha^{-1} when the price of switchgrass was \$50 Mg^{-1}; however, at the two higher switchgrass prices the profit-maximizing N rate was 67 kg N ha^{-1}. For the MDSU soil type/landscape, the profit-maximizing N rate decreased to 67 kg N ha^{-1} for all the switchgrass prices. The profit-maximizing N rate for the PDFP soil type/landscape was 0 kg N ha^{-1} at \$50 Mg^{-1}, but was 67 kg N ha^{-1} at both \$70 Mg ha^{-1} and \$90 Mg ha^{-1}.

Across soil types/landscapes, the profit-maximizing N rate was sensitivity to the price of N and the price of switchgrass, but not all soil types/landscapes had equally sensitive profit-maximizing N rate to the price changes in N and switchgrass. The WDFP soil type/landscape did not show sensitivity to prices until the lowest price of switchgrass and the highest price of N were reached. All other soil types/landscapes showed a change in the profit-maximizing N rate when the price of N increased from \$0.70 kg N ha^{-1} to \$1.30 kg N ha^{-1}. Haque et al. [42] and Aravindhakshan et al. [43] also present a sensitivity analysis of profit-maximizing N rates for switchgrass production in Oklahoma at one location. We add to this literature by demonstrating how the profit-maximizing N rate can vary across soil types/landscapes. Additionally, we demonstrate under certain circumstances apply no N maximizes profits.

6. Conclusions

The objectives of this research were to determine the (1) yield- and (2) profit- maximizing N rates for switchgrass grown on four different soil types/landscapes in Tennessee. We analyzed data from an experiment conducted at Milan, Tennessee from 2005 to 2010 on four soil types/landscapes common to Tennessee ranging from a poorly-drained flood plan to a well-drained upland. Mixed model were used to perform ANOVA on yield and net returns across the four experimental N rates for each soil type/landscape. A paired differences test was implemented to determine the yield-maximizing N rate and the profit-maximizing N rate. The results from this study provide further insight into how soil types/landscapes can change the agronomic and economic optimal N rates in switchgrass production.

The N rates that maximized average yield were different across the four soil types/landscapes, and the average yields also varied across the four soil types/landscapes. The yield-maximizing N rates were 67, 134, 134, and 200 kg N ha^{-1} for the WDFP, WDLU, MDSU, and PDFP soil types/landscapes, respectively. These rates fall within the range of estimates in the literature that has measured yield-maximizing N rates for switchgrass production. Measuring differences in yield-maximizing N rates across soil types/landscapes contributes to the literature by demonstrating the impact of soils/landscapes on switchgrass yields under the same weather conditions [44,45].

Furthermore, we demonstrate how soil types/landscapes influence the profit-maximizing N rate, which extends the literature. We perform an extensive sensitivity analysis with three switchgrass prices and three N prices. For the WDFP soil type/landscape, the profit-maximizing N rate ranged from 0 kg N ha^{-1} to 67 kg N ha^{-1}. The profit-maximizing N rate for the WDLU soil type/landscape and MDSU soil type/landscape ranged from 0 kg N ha^{-1} to 134 kg N ha^{-1}. For the PDFP soil type/landscape, the profit-maximizing N rate ranged from 0 kg N ha^{-1} to 200 kg N ha^{-1}. This suggests that profit-maximizing N rates for all soil types/landscapes were not equally sensitive to prices changes, which is a unique contribution to the literature. The majority of price combinations in the sensitivity analysis validates Heaton et al. [19]'s finding that switchgrass requires an annual application of N to produce yields large enough to make its production economically viable, but under certain price scenarios producers are better off not applying N.

Additional research is needed to find the most suitable functional form to measure switchgrass yield response to N. Using a parametric approach to find optimal N rates will be helpful in recommending more exact profit-maximizing N rates to switchgrass producers in Tennessee. In addition, further research is needed to determine whether the optimal net returns found in this research provide higher net returns than the best alternative crop on each soil type/landscape.

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 the anonymous reviewers for comments on an earlier draft. This research was made possible with partial funding from Department of Energy Project DE-FG36-04GO14219, the UT Switchgrass Demonstration Project, and the CSREES/USDA through Hatch Project TEN00348.

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