Switchgrass nitrogen response and estimated production costs on diverse sites

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Abstract

Switchgrass (Panicum virgatum L.) has been the principal perennial herbaceous crop investigated for bioenergy production in North America given its high production potential, relatively low input requirements, and potential suitability for use on marginal lands. Few large trials have determined switchgrass yields at field scale on marginal lands, including analysis of production costs. Thus, a field-scale study was conducted to develop realistic yield and cost estimates for diverse regions of the USA. Objectives included measuring switchgrass response to fertility treatments (0, 56, and 112 kg N ha⁻¹) and generating corresponding estimates of production costs for sites with diverse soil and climatic conditions. Trials occurred in Iowa, New York, Oklahoma, South Dakota, and Virginia, USA. Cultivars and management practices were site specific, and field-scale equipment was used for all management practices. Input costs were estimated using final harvest-year (2015) prices, and equipment operation costs were estimated with the MachData model ($2015). Switchgrass yields generally were below those reported elsewhere, averaging 6.3 Mg ha⁻¹ across sites and treatments. Establishment stand percent ranged from 28% to 76% and was linked to initial year production. No response to N was observed at any site in the first production year. In subsequent seasons, N generally increased yields on well-drained soils; however, responses to N were nil or negative on less well-drained soils. Greatest percent increases in response to 112 kg N ha⁻¹ were 57% and 76% on well-drained South Dakota and Virginia sites, where breakeven prices to justify N applications were over $70 and $63 Mg⁻¹, respectively. For some sites, typically promoted N application rates may be economically unjustified; it remains unknown whether a bioenergy industry can support the breakeven prices estimated for sites where N inputs had positive effects on switchgrass yield.

Keywords: bioenergy, biomass, economics, fertility, field scale, marginal land, Panicum virgatum, yield

Introduction

Switchgrass (Panicum virgatum L.) has been the principal perennial herbaceous crop investigated for bioenergy production in North America (McLaughlin & Kszos, 2005; Parrish & Fike, 2005). High productivity, adaptability to marginal sites, and low nutrient input requirements make the species attractive for limited-input bioenergy systems (Wright & Turhollow, 2010). Potential to grow switchgrass and other ‘second-generation’ perennial bioenergy crops on marginal land has been a particular point in their favor, as many consider these crops a way to avoid competition for arable lands that could be used to grow food and fiber crops (Hill et al., 2006; Gopalakrishnan et al., 2011). Although there is strong debate on the subject (Searchinger et al., 2008), some research also suggests that biomass-to-energy schemes using marginal lands would provide substantial conservation services, particularly in terms of...
carbon sequestration and other ecosystem benefits (Liebig et al., 2005; Bhardwaj et al., 2011; Hartman et al., 2011; Gelfand et al., 2013).

For a developing bioenergy industry, there will be substantial economic risk associated with commitment of scarce farmland resources to energy crop production. Apart from the learning curve necessary for efficient production management of a new crop, investment costs must be recouped over a multiple-year rotation providing little certainty of profitable returns. Potential difficulty in switchgrass establishment implies higher investment costs and greater risks for producers. If a bioenergy crop is to be a profitable alternative to existing row crop or forage production, it must satisfy at least the following conditions:

1. The crop must generate relatively high yields and net returns to outbid existing crops for scarce land resources, and to offset high transport costs of shipping a bulky product.

2. To reduce annual operating costs and generate profitable annual returns, crop production following establishment must require only limited chemical and other operating inputs given the low value of biomass.

3. Because bioenergy crops are usually bulky, and transportation costs may make a large portion of farm-to-fuel production costs, a bioenergy crop buyer must be located within a relatively short distance from the production location. A single buyer will have the incentive each harvest cycle to reduce offered bioenergy crop prices, creating considerable risk for producers.

Although some marginal sites may be suitable for producing biomass, the typically low productivity associated with such soils may cause concern for their ability to support herbaceous bioenergy production systems profitably. This may be particularly true for switchgrass systems, given the plant’s reputation of being challenging to establish (Fike et al., 2014) particularly in the face of weed competition. Excessive weed competition at establishment may lower yield or increase production costs (due to more interventions), or both. Even on ‘clean’ sites that require few inputs for establishment, the time required to reach full productivity can vary widely, and production guides often suggest that switchgrass stands may not be fully established (i.e. not fully productive) until the third growing season (Teel et al., 2003; Wolf & Fiske, 2009). However, using newer herbicides (Mitchell et al., 2010), accounting for seed quality (i.e. dormancy and vigor) in the seeding process (Mitchell & Vogel, 2012), and following improved establishment guidelines such as proper planting date (Mitchell et al., 2013) have accelerated switchgrass establishment success, often resulting in harvestable yields at the end of the planting year and stands at 75–100% full production in the first full growing season after planting.

The current research reports results of a multiyear examination of switchgrass yields on marginal sites treated with increasing levels of nitrogen (N) fertilization. Fertility inputs, particularly N, generally are not recommended for switchgrass during the establishment year (Teel et al., 2003; Wolf & Fiske, 2009; Mitchell et al., 2013). Responses to phosphorus and potassium have been shown to have limited impact (McKenna & Wolf, 1990), and responses to N can be quite variable (e.g. see review by Parrish & Fike, 2005). Variation among study results in response to fertility inputs may reflect differences in soil quality, and it is possible that marginal sites of low fertility may require greater nutrient inputs to support high levels of biomass production.

Generating reasonable estimates of production costs and yield potential on marginal sites is critical for determining the economic and social sustainability of such enterprises. Several authors have attempted to model how implementing large-scale energy cropping systems will affect the costs not only of bioenergy, but of other commodities in the context of marginal and non-marginal land use (Searchinger et al., 2008; Cai et al., 2011; Boyer et al., 2012; Zhang et al., 2013). The yield estimates used in such modeling exercises affect many factors in the system, including acreage needed, logistics costs (for handling and transport), and refinery size. However, such efforts inherently are challenged by the fact that they rely on yield data taken almost exclusively from small-plot research.

Although informative, small-plot research is less likely to reflect the variability of field-scale production or the losses or changes in biomass quality typical of harvest and storage operations at the field scale (Coble, 1989; Lötjönen, 2008; Bow & Muir, 2010; Meehan et al., 2013). Potential sources of upward bias with plot research include the siting of plots on better soils as well as atypically small harvest losses during cutting and collection given the harvest technologies deployed at a plot scale. Thus, while size per se was not perceived as a significant source of upward bias in plot studies (Wullschleger et al., 2010), such methods may not provide realistic production estimates relevant to a commercial-scale production system. This risk of upward bias with small-plot data may be even greater on marginal sites given that such lands often present additional logistic challenges to production and harvest such as steep slopes or poor drainage.

Data on switchgrass production at field scale are limited, especially on marginal sites. To our knowledge, only one large-scale (multi-acre), multisite research study has been reported for switchgrass production on

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marginally productive sites (Schmer et al., 2008). Average annual yields ranged from 5.2 to 11.1 Mg ha$^{-1}$ on dryland sites located across the northern Great Plains (from southern Nebraska to northern North Dakota).

Along with appropriate yield estimates, suitable projections of scaled-up production costs will be critical to define the economic realities of second-generation bioenergy cropping systems. The ability to estimate production costs and system profitability at the farm level will be especially affected by one’s management assumptions concerning such major costs as fertility treatments and harvest costs. For example, fertility (especially N fertility) is one of the most frequently explored variables for switchgrass production (Sanderson & Reed, 2000; Vogel et al., 2002; Lemus et al., 2008; Guretzky et al., 2011; Liu et al., 2013, 2014) as it represents one of the largest management and environmental costs (Hall et al., 2011).

Effects of N fertilization on switchgrass production are particularly important given the broad range of responses that have been reported (Parrish & Fike, 2005) and the resulting variable impacts on profitability. Generally, switchgrass productivity in response to N has been reported to be low, but this has depended on genotype, on site conditions such as precipitation and soils, and on management factors such as harvest frequency and timing. Perhaps these variable factors – and a somewhat inconsistent response to N – have been a motivator for the recommendation that producers fertilize to replacement. This was the approach of Schmer et al. (2008), whose 10 producer–collaborators individually chose to apply N at rates ranging from 0 to 212 kg ha$^{-1}$.

Stands were managed under a single, end-of-season harvest following senescence; the mean annual N application rate across all farms in the production years (2–5) was 74 kg ha$^{-1}$. In further analysis of the field-level trials, Perrin et al. (2008) showed mean production costs for the five lower- and five higher-cost sites were $51.95 and $88.25 Mg$^{-1}$, respectively, with a mean cost of $65.86 Mg$^{-1}$ across all farms. It cannot, however, be ascertained from the research whether the N fertilization rate was either biologically or economically optimal. Boyer et al. (2012) estimated switchgrass profit-maximizing yield response to N on four landscapes in TN and determined that the best fit varied across landscapes, ranging from 62 to 108 kg N ha$^{-1}$ on upland sites, and 155–200 kg N ha$^{-1}$ on poorly drained floodplain sites.

In an effort to develop realistic yield and cost estimates for diverse regions of the country, the US Department of Energy implemented a series of regional production studies to analyze several potential energy crops through the Sun Grant Initiative’s Regional Feedstock Partnership. The major objectives of the work reported herein are to determine switchgrass biomass yield in response to N and corresponding estimates of production costs in field-scale studies located on marginal sites with diverse soil and climatic conditions. Additional objectives of this research (such as management effects on soil carbon and N and on feedstock quality) have been reported elsewhere (Owens et al., 2013; Hong et al., 2014). This study describes findings on establishment, crop yield, and switchgrass production costs over 2009–2015 on selected sites in Iowa, New York, Oklahoma, South Dakota, and Virginia, USA.

Materials and methods

Establishment protocol and first-year management

Switchgrass stands were established in 2008 (at all sites except Iowa and in 2009 at Iowa). Site descriptions, along with soil and climatic characteristics for each site, are presented in Tables 1 and 2. Iowa, South Dakota, and Virginia soil series ranged from moderately well drained to well drained, and OK and NY soil series were poorly drained fields (Table 1). Land management practices and cultivar selections (Table 3) were not identical across sites but rather were based on regionally appropriate guidelines for switchgrass production, including use of the best available cultivars. Switchgrass stands were treated with herbicides as needed (Tables 3 and 4) and were not fertilized or harvested in the establishment year.

Fertility and harvest management

Beginning the year after planting, switchgrass plots (four replicates; minimum plot size = 0.39 ha) were fertilized using local farm or commercial application equipment (Table 4) and locally available inorganic N sources. Nitrogen was applied as ammonium sulfate in New York and Virginia and as urea in Iowa, Oklahoma, and South Dakota at rates of 0, 56, or 112 kg ha$^{-1}$. At all sites, plots received additional herbicide treatment during the first crop year. Herbicides also were applied in 2010 and 2011 in Oklahoma and South Dakota. No site received herbicides during the 2012–2014 cropping seasons. A broadleaf herbicide was applied in 2015 at the Iowa site.

Plot harvest dates also varied by site. Harvests began as early as October, following the first killing frost (New York). Harvests were planned for January in Virginia but occurred as late as March to have sufficiently firm (i.e. dry or frozen) ground. Entire plots at all sites were harvested with conventional hay-making equipment (Table 4), but harvest equipment and practices varied by state.

Productivity measures

To determine establishment-year stand percentages, four random measures per plot were made using a 0.75-m $\times$ 0.75-m metal grid following Vogel & Masters (2001). Briefly, each grid contained 25 15-cm $\times$ 15-cm cells, and the sum of cells in which switchgrass was counted as present (from the four
Statistical analysis of yields

At all locations, plots were arranged in a randomized complete block design with four replications. Production data were analyzed using the PROC MIXED procedure of SAS (version 9.3; SAS Institute, Cary NC, USA). Year was treated as a repeated measure as the same plots were used at each location in each year, and an autoregressive covariance structure was used for the overall model. The Tukey–Kramer test and the PDMMIXX macro (Saxton, 1998) were used to determine and designate treatment differences. Linear and quadratic contrasts were also performed to determine the nature of response to N treatment. Data reported are LS means, and significance was declared for P values less than 0.05.

Economic assessment measures

In some states, research plots were located on university farms, while in other states, farmers were contracted to raise switchgrass under researcher supervision. Field activity records were to be kept throughout the establishment and production years 2008–2015, including dates that activities were performed; labor, tractor, and equipment hours; fuel use; and quantities of inputs used (seed, fertilizer, and herbicides). Labor and management practices and equipment employed varied widely across states over the 8 years. Some hours and cash costs were not consistently recorded across states and years because of changes in supervisory personnel, and only a few prices paid for herbicides and fertilizers were recorded over the course of the research.

The economic assessment provided here is designed to estimate switchgrass per-ha and per-Mg production. The format of the enterprise budgets follows Mooney et al. (2009) and Mironovski et al. (2010). The principal factors affecting production cost, land cost, the cost of operating inputs, the cost of power equipment and implements, and other costs reflect management and owner investments, risk, and opportunity costs. Machinery and equipment costs reflect both operating and overhead charges. Establishment-year costs are prorated over 11 years (estimated establishment and production period until reseeding). The costs of harvest staging, storage, and transport are not considered, as the focus of the current research is only on production costs.

Input prices. Not all cooperators recorded the price paid for each input applied to each plot in all years, and each state’s team faced varying prices for inputs. In some cases, some inputs were provided at reduced prices, while other input

| State (county) | Latitude; longitude* | Soil series | Soil description | Mean plot size, ha |
|----------------|----------------------|-------------|------------------|-------------------|
| Iowa (Story)   | 41.98; –93.70        | Clarion     | Fine-loamy, mixed, superactive, mesic Typic Hapludolls | 0.61 |
|                |                      | Nicollet    | Fine-loamy, mixed, superactive, mesic Aquic Hapludolls |      |
|                |                      | Canisteo    | Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls |      |
|                |                      | Harps       | Fine-loamy, mixed, superactive, mesic Typic Calciaquolls |      |
|                |                      | Webster     | Fine-loamy, mixed, superactive, mesic Typic Endoaquolls |      |
| New York (Tompkins) | 42.46; –76.46     | Erie        | Fine-loamy, mixed, active, mesic Aeric Fragiueptes | 0.39 |
|                |                      | Langford    | Fine-loamy, mixed, active, mesic Typic Fragiuclods |      |
| Oklahoma (Muskogee) | 35.74; –95.64    | Parsons     | Fine, mixed, active, thermic Mollic Albaqualfs | 0.40 |
|                |                      | Carytown    | Fine, mixed, active, thermic Albic Natraqualfs |      |
|                |                      | Taloka      | Fine, mixed, active, thermic Mollic Albaqualfs |      |
| South Dakota (Day) | 45.27; –97.84    | Aastad      | Fine-loamy, mixed, superactive, frigid Pachic Argiudolls | 0.78 |
|                |                      | Forman      | Fine-loamy, mixed, superactive, frigid Calcic Argiudolls |      |
|                |                      | Buse        | Fine-loamy, mixed, superactive, frigid Typic Calciudolls |      |
|                |                      | Nutley      | Fine, smectitic, frigid Chromic Hapluderts |      |
|                |                      | Sinai       | Fine, smectitic, frigid Typic Hapluderts |      |
|                |                      | Barnes      | Fine-loamy, mixed, superactive, frigid Calcic Hapludolls |      |
| Virginia (Pittsylvania) | 36.93; –79.19 | Creedmoor   | Fine, mixed, semi-active, thermic, Aquic Hapludults | 0.39 |
|                |                      | Mayodan     | Fine, mixed, semi-active, thermic, Typic Hapludults |      |

*Latitude and longitude are expressed in decimal degrees.


Table 2  Average yearly total and 30-year mean precipitation and daily maximum temperatures for five sites used in a long-term field-scale switchgrass production study

| State (county)     | Year | Yearly total precipitation, mm | 30-year Mean | State (county)     | Year | Average daily temperature, °C | 30-year Mean |
|--------------------|------|--------------------------------|--------------|--------------------|------|-------------------------------|--------------|
|                    |      | 2009                          | 2010         | 2011              | 2012 | 2013  | 2014  | 2015 | Mean* | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Mean* |
| Iowa (Story)       | –    | –                             | 848          | 980               | 1301 | 834   | 991   | 978  | 858   | 937  | 7.5  | 8.7  | 8.8  | 9.6  | 8.0  | 7.0  | 7.7  | 8.1  |
| New York (Tompkins)| 1079 | 848                           | 971          | 659               | 1103 | 983   | 1956  | 1137 | 15.3 | 16.0 | 17.3 | 14.6 | 14.4 | 15.4 | 15.5 |
| Oklahoma (Muskogee)| 716  | 677                           | 538          | 585               | 617  | 432   | 499   | 619  | 5.1   | 6.8  | 6.2  | 8.3  | 4.9   | 4.9  | 7.9  | 6.4  |
| South Dakota (Day)| 1424 | 1215                          | 1074         | 1011              | 1391 | 1173  | 1363  | 1144 | 12.5  | 12.9 | 13.4 | 13.5 | 12.0  | 11.3 | 12.9 | 12.8 |
| Virginia (Pittsylvania) | –    | –                             | –            | –                 | –    | –     | –     | –    | –     | –    | –    | –    | –     | –    | –    | –    |

*Means for precipitation and temperature determined over the period from 1986 to 2015.

Prices were elevated because of local or temporal shortages. If actual prices paid were used in calculating economic costs, the differences in resulting breakeven costs would be attributable to both agronomic and local/state price variation, so prices of inputs were thus collected from a common source. Principal input price sources are for herbicides (S. Hagood 2013, personal communication) and for fertilizer (USDA-NASS, 2013a). To distinguish large-plot production effects of varying N inputs, final harvest-year (2015) prices were used to estimate all input costs. Years 2009–2014 costs were inflated using the Index of Production Prices Paid (USDA-NASS, 2013c) to report and compare prices in 2015 dollars.

Machinery and equipment. There was insufficient information available to estimate operating and overhead for each research site across all years. In addition, some power units and equipment combinations may have been selected more for their availability than for their cost efficiency. Machinery and equipment costs were estimated with the MachData model (Lazarus, 2016), which uses economic engineering-based estimates of per-hour and per-acre costs of labor, tractor, and equipment use. This machinery cost estimator is used widely by farm management advisors and farm managers (Myhre, 2010; Venuto & Daniel, 2010; Maung & Gustafson, 2013). The results indicate a representative cost per activity rather than that specifically incurred in the field – or in this case, on the research plot. Using this approach, machinery and equipment used in the research can be matched closely with MachData to provide an estimate of field activity costs at a commercial farm scale, emphasizing the relative agronomic impacts of N fertilization and contrasts between states.

Miscellaneous costs. Costs of selected activities were estimated as the price of custom contracted activities. Nitrogen fertilizer applications were charged at custom rates, and baling was charged at a per-bale rate, both of which were set equal to the midpoint of custom rates reported in Edwards & Johanns (2012). Additional costs that must be considered are farmland cash rent, operating loan expenses, and labor cost. Farmland opportunity cost was estimated by annual own-county cash rent survey value (USDA-NASS, 2013b). To reflect the marginal nature of these sites, the rental rate was estimated at the midpoint between reported county cropland and pastureland rates. Operating loan interest expense was estimated for all fertilizer and chemical purchases for a term of 6 months at the assumed interest rate of 6% per annum. Finally, skilled labor for machinery operation was priced at $15 h⁻¹.

Results

Three important results of this research – yield, production cost ha⁻¹, and production cost Mg⁻¹ – shed light on the economic feasibility of switchgrass production on these marginal sites.

Production responses by site, year, and N treatment

Stand percentages were determined in 2009 or 2010 before the initiation of fertility treatments (Table 5), and percentages ranged from 76% (Iowa) to 28% (Virginia).

Production responses were affected by significant year x site, year x treatment, and site x treatment interactions. Thus, data were analyzed and are presented by site. To encapsulate the results, yield response to increasing N applications was not observed at any site during the first production season. Over all growing seasons, yield responses in Iowa, South Dakota, and Virginia were linear or quadratic or both, suggesting more limited response to N at higher rates. In contrast, biomass yields were largely unresponsive to N in Oklahoma and negative in New York.
significant in crop years 2011 through 2015, with stronger response to N the last 2 years. Over the six crop years, yield responses to increasing N were both significantly linear and quadratic ($P < 0.0001$), indicating yields increased at a decreasing rate with greater N inputs.

**New York.** Yields varied by year and treatment ($P < 0.0001$) in New York and generally were consistent over time (i.e. no treatment by year interaction). Yields (averaged across treatments) were lowest in 2009 (crop year 1; Table 5). Aside from an exceptional production year in 2013 (mean across treatments = 8.95 Mg ha$^{-1}$), yields averaged across treatments for the remaining crop years were fairly uniform and within a range of 6.2–6.8 Mg ha$^{-1}$. Significant variability among N treatments was observed only in 2010, when plots receiving no N fertility treatments had greater yields (unexpectedly) than plots receiving the higher (112 kg N ha$^{-1}$) N treatment (year *×* treatment interaction; $P < 0.02$). Across years, the mean response pattern to N in New York was both negatively linear and quadratic ($P < 0.0001$), with decreasing yields at higher rates of N application.

**Oklahoma.** Year effects ($P < 0.0001$) were the most important driver of switchgrass production in Oklahoma. Yields largely were insensitive to N treatment ($P = 0.4387$), although a year *×* treatment interaction ($P = 0.0111$) was observed. Following the 2009 production season, yield increases averaged about 1.3 Mg ha$^{-1}$ relative to average yields from the previous crop year, and yields in 2013 (8.74 Mg ha$^{-1}$) were 5.29 Mg ha$^{-1}$ (153%) greater than yields of biomass produced in 2009 (3.45 Mg ha$^{-1}$).

**South Dakota.** Yield responses to treatments ($P < 0.0001$) were consistent across years in South Dakota. Although yields changed over time (year effect; $P < 0.0001$), there were no year *×* treatment interactions ($P = 0.3617$). From the first to the second crop years, mean yields increased 87% (from 2.39 to 4.46 Mg ha$^{-1}$). Excepting the first (2009) and last (2015) crop years, yields were quite consistent at the South Dakota site. Average yield across treatments and years from 2010 to 2014 was 4.33 Mg ha$^{-1}$, and the difference from average yield within this period was never larger than 7% (4.63 Mg ha$^{-1}$ in 2012). However, an average yield decline of 19% was observed in the 2015 crop year relative to the average of the 2010–2014 crop years. Averaged over all crop years, increasing fertilizer application rates to 56 and 112 kg ha$^{-1}$ resulted in 45% and 57% greater biomass yields relative to controls. For most years, however, there were no differences in yield
Table 4  Herbicide and nitrogen inputs and field operations by site-year following establishment of a long-term field-scale switchgrass production study

| Site         | Years* | Herbicides                                                | Rate       | N source†‡ | Harvest†‡ | Baler type†‡ |
|--------------|--------|-----------------------------------------------------------|------------|------------|------------|--------------|
| Iowa         | 2015   | 2,4-D                                                     | 2.3 L ha⁻¹ | Urea       | Mow + rake | Square       |
| New York     | 2009   | Glyphosate, Diacamba                                     | 2.3 L ha⁻¹ | Ammonium sulfate | Mow + rake | Square       |
| Oklahoma     | 2009   | Quinclorac, 2,4-DB                                       | 370 g ha⁻¹ | Urea       | Mow + rake | Square       |
|              | 2010   | 2,4-D (2 applications)                                    | 9.4 L ha⁻¹ |            |            |              |
|              | 2011   | Chaparral (potassium salt of 2-pyridine carboxylic acid, 4-amino-3,6-dichloro + Metsulfuron methyl | 0.17 L ha⁻¹ |            |            |              |
| South Dakota | 2009   | Clopyralid MEA salt + fluoroxypr 1 methylheptyl ester    | 1.2 L ha⁻¹ | Urea       | Mow        | Round        |
|              |        | Quinclorac                                               | 350 g ha⁻¹ |            |            |              |
|              |        | Atrazine                                                 | 2.3 L ha⁻¹ |            |            |              |
|              |        | Diacamba                                                 | 420 g ha⁻¹ |            |            |              |
|              |        | 2,4-D amine                                              | 1.2 L ha⁻¹ |            |            |              |
|              | 2010   | Grazon                                                   | 3.5 L ha⁻¹ |            |            |              |
|              |        | Atrazine 4L                                              | 4.7 L ha⁻¹ |            |            |              |
|              | 2011   | Glyphosate, 2,4-D amine                                  | 1.2 L ha⁻¹ |            |            |              |
|              |        | Class act                                                | 1.2 L ha⁻¹ |            |            |              |
|              |        | Quinclorac                                               | 350 g ha⁻¹ |            |            |              |
|              |        | 2,4-D amine                                              | 2.3 L ha⁻¹ |            |            |              |
| Virginia     | 2009   | Glyphosate, 2,4-D                                        | 4.7 L ha⁻¹ | Ammonium sulfate | Mow + rake | Round        |
|              |        | Quinclorac                                               | 1.2 L ha⁻¹ |            |            |              |

*Years designate times for herbicide applications only. Nitrogen source, harvest practices, and bale type remained the same within a site over the study.
†Nitrogen rates were 0, 56, and 112 kg ha⁻¹.
‡Management practice used in all years within sites.

between the 56 and 112 kg ha⁻¹ application rates. This ‘plateau’ effect resulted in significant (P < 0.0001) linear and quadratic responses to N treatment.

Virginia. Yields in Virginia were affected both by years and treatments (P < 0.0001), and there were no year × treatment interactions (P = 0.8024). Yields nearly doubled from 2009 to 2010 (3.56−6.85 Mg ha⁻¹) and averaged 6.76 Mg ha⁻¹ over years and treatments. Averaged over crop years, yield increases in response to N fertilizer application rates of 56 and 112 kg ha⁻¹ were 41% and 77% above the control, resulting in strong linear and quadratic responses to fertility (P < 0.0001).

Production costs and economics of N fertilization

Economic results include production cost ha⁻¹ and production cost Mg⁻¹. These production costs are presented by state, year, and N treatment in Tables 6–10. Mean total production cost ha⁻¹ in 2015 dollars averaged $452 ha⁻¹ and ranged from $394 (South Dakota) to $536 ha⁻¹ (New York), which had the lowest and highest harvest costs, respectively. Production costs are determined not only by production activities, but also by establishment costs, land rent, and yields. The highest per-ha cost in New York was 36% greater than that in South Dakota. New York had the highest prorated establishment costs ($64 ha⁻¹) and the highest harvesting costs ($267 ha⁻¹) among sites. Both land charges and preharvest operating expenses were greatest in South Dakota, but these were more than offset by the very low harvest charges for that site (Table 9). For comparative purposes, the mean weighted average annualized cost of production reported in Perrin et al. (2008) was $453 ha⁻¹ ($2015), almost identical to the mean production cost reported here. However, the per-Mg production cost of biomass in this study is higher than that of Perrin et al. (2008) because their estimates included staging and storing costs, which were not estimated in this study.
NITROGEN RESPONSES AND PRODUCTION COSTS

Table 5 Establishment-year stand estimates and crop year yield estimates

| State (locality) | Year | Stand, % | Yield, Mg ha\(^{-1}\)* | Nitrogen application, kg ha\(^{-1}\) |
|-----------------|------|----------|------------------------|-------------------------------------|
| Iowa (Ames)     | 2009 | –        | –                      | 0, 56, 112, SE                       |
|                 | 2010 | 75.9     | 6.96                   | 6.73, 7.35, 0.377                   |
|                 | 2011 | –        | 6.31                   | 7.38a, 7.05ab, 0.280                |
|                 | 2012 | –        | 6.15b                  | 7.99a, 8.25a, 0.397                 |
|                 | 2013 | –        | 6.72b                  | 9.14a, 10.22a, 0.641                |
|                 | 2014 | –        | 3.82c                  | 5.52b, 7.16a, 0.360                 |
|                 | 2015 | –        | 5.95c                  | 8.26b, 9.64a, 0.397                 |
|                 | Mean | –        | 6.00b                  | 7.50a, 8.28a, 0.284                 |
| New York (Ithaca) | 2009 | 60.1     | 6.19                   | 6.11, 6.40, 0.352                   |
|                 | 2010 | –        | 6.72a                  | 6.14b, 5.41c, 0.125                 |
|                 | 2011 | –        | 7.81a                  | 6.10b, 6.79ab, 0.460                |
|                 | 2012 | –        | 6.66                   | 6.96, 6.74, 0.130                   |
|                 | 2013 | –        | 9.42                   | 8.84, 8.60, 0.683                   |
|                 | 2014 | –        | 7.04                   | 6.28, 6.01, 0.411                   |
|                 | 2015 | –        | 6.95a                  | 6.40b, 6.67ab, 0.141                |
|                 | Mean | –        | 7.25a                  | 6.69b, 6.70b, 0.239                 |
| Oklahoma (Muskogee) | 2009 | 47.3     | 3.13                   | 3.29, 3.92, 0.394                   |
|                 | 2010 | –        | 4.62                   | 4.97, 4.84, 0.182                   |
|                 | 2011 | –        | 7.34ab                 | 6.11b, 7.36a, 0.399                 |
|                 | 2012 | –        | 7.82                   | 8.71, 7.93, 0.287                   |
|                 | 2013 | –        | 8.81                   | 9.11, 8.31, 0.394                   |
|                 | 2014 | –        | 7.66a                  | 7.36ab, 6.93b, 0.244                |
|                 | 2015 | –        | 5.86                   | 7.16, 6.09, 0.404                   |
|                 | Mean | –        | 6.46                   | 6.67, 6.48, 0.359                   |
| South Dakota (Bristol) | 2009 | 29.0     | 1.82                   | 2.48, 2.87, 0.353                   |
|                 | 2010 | –        | 3.59b                  | 4.98a, 4.82a, 0.460                 |
|                 | 2011 | –        | 3.29b                  | 4.42a, 4.59a, 0.214                 |
|                 | 2012 | –        | 3.48b                  | 5.02a, 5.41a, 0.322                 |
|                 | 2013 | –        | 3.04c                  | 4.57b, 5.40a, 0.174                 |
|                 | 2014 | –        | 2.82b                  | 4.66a, 4.94a, 0.266                 |
|                 | 2015 | –        | 2.54c                  | 3.71b, 4.30a, 0.145                 |
|                 | Mean | –        | 2.94b                  | 4.26a, 4.62a, 0.194                 |
| Virginia (Gretna) | 2009 | 27.8     | 2.73                   | 3.82, 4.14, 0.532                   |
|                 | 2010 | –        | 4.82b                  | 6.67ab, 9.05a, 1.055                |
|                 | 2011 | –        | 4.71b                  | 6.39b, 8.48a, 0.697                 |
|                 | 2012 | –        | 5.63b                  | 8.37a, 10.53a, 1.080                |
|                 | 2013 | –        | 4.23b                  | 6.78ab, 8.38a, 1.011                |
|                 | 2014 | –        | 6.40b                  | 8.29ab, 10.23a, 1.101               |
|                 | 2015 | –        | 5.42b                  | 7.73a, 9.07a, 0.759                 |
|                 | Mean | –        | 4.85c                  | 6.86b, 8.56a, 0.660                 |

*Means within rows with different letter designations are significantly different (P < 0.05).

Mean production costs Mg\(^{-1}\) dry matter varied widely: from $65 Mg\(^{-1}\) in Oklahoma to $99 Mg\(^{-1}\) in South Dakota. Costs per Mg in Oklahoma, New York, and Virginia were intermediate ($65–$73 Mg\(^{-1}\)). Although the New York site had the highest production costs per hectare, costs were offset by relatively high yields, resulting in a per-Mg cost of $73. South Dakota county rental rates were much higher than in other states, likely reflecting land competition from corn production, and switchgrass yields were relatively low. Thus, the South Dakota unit cost of production was 66% greater than that of Oklahoma, which also benefited from greater average yields (7.1 Mg ha\(^{-1}\)).

Discussion

Production responses by site, year, and N treatment

Stand density percentages in South Dakota and Virginia were low (<30%) compared to recommendations for successful biofuel crop establishment (≥40% in Schmer et al., 2006). This likely was a factor in the relatively low yields produced during the first harvests in 2009 at all sites except New York. However, there may be some questions about the effect of stand density on total productivity over time, given the limited effects of wide row spacing reported on biomass yield (Ma et al., 2001; Foster et al., 2012).

Iowa. Lack of yield response in year 1 may in part reflect the high initial soil N status at the site (Owens et al., 2013) from previous management (Table 3). Soils also received relatively high N inputs during the establishment year, because switchgrass was seeded along with a maize (Zea mays) crop. Our approach was to use regionally specific best management practices as guidelines for establishment. Seeding switchgrass with maize both allowed the use of atrazine, an herbicide labeled for maize (as per Hintz et al., 1998), and provided for some productivity from the site during the period of establishment. Although a plot study by Heggenstaller et al. (2009) indicated yields could be much higher (12.5 Mg ha\(^{-1}\)) than these results— and optimized with 140 kg N ha\(^{-1}\) — similar yields and responses to N inputs were observed by Lemus et al. (2008a) in a field-scale study in southern Iowa. However, greater yields may have been achievable with adapted lowland switchgrass varieties (Lemus et al., 2002).

New York. These yield data for the upland cultivar Cave-In-Rock were similar to those reported in another New York study by Wright (2007), in which switchgrass production ranged from 4.17 to 8.76 Mg ha\(^{-1}\) and with the lower yields occurring on poorly drained sites. Yields also were within the range of results from plot studies in surrounding regions — about 7.4 Mg ha\(^{-1}\) in Pennsylvania, USA, and 11–12 Mg ha\(^{-1}\) in Quebec, Canada (Mada-kadze et al., 1999a,b; Adler et al., 2006). Reasons for the observed yield decline with added fertility are not apparent, as lodging in these plots was not observed.
Oklahoma. Blackwell switchgrass yields in this study were about three to four times the yields of a mature Blackwell stand in another study in Oklahoma (Rogers et al., 2012). Average N rates in the Rogers et al. study (78 kg ha\(^{-1}\)) were similar to ours, but the researchers harvested twice per season, which likely would increase yield due to greater removal of nonstructural carbohydrates, proteins and nonprotein N, and minerals. It is likely that use of a lowland ecotype would have resulted in greater biomass (and lower production costs) in our study. Rogers et al. (2012) also tested Alamo switchgrass and reported average yields approaching 18 Mg ha\(^{-1}\). Again, this was with two-cut management. Studies from the region suggest that although quite a wide range of yield responses (from about 6 to 17 Mg ha\(^{-1}\)) is possible, a single harvest per season more typically would average around 12 or 13 Mg ha\(^{-1}\) (Thomason et al., 2004; Aravindhakshan et al., 2011; Keruing et al., 2012a,b; Makaju et al., 2013).

South Dakota. Large year-to-year increases in biomass at South Dakota likely reflect the low initial stand density at the site. Mean yields across all years and treatments (3.94 Mg ha\(^{-1}\)) in South Dakota were lowest among the five sites reported here. However, yields were similar to those from other studies in the region using switchgrass monocultures and mixed stands (Mulkey et al., 2006, 2008; Lee et al., 2007, 2009). Unlike in New York and Oklahoma, evidence of a positive yield response to N fertilization was observed in all but the first crop year (2009). Lack of differences in yield between the 56 and 112 kg ha\(^{-1}\) N application rates is similar to results from the region reported by Mulkey et al. (2006) and may reflect an inability to use the additional N given the inherently lower productivity of the site. Yield measures at this site also were the most variable. This may have been a function of its being the only site both managed and measured by the producer collaborator, but it certainly reflects the challenge of producing biomass in the Southeast (Cundiff et al., 2009), given the region's smaller, irregularly shaped land parcels.

Table 6 Iowa annual production costs*† for Cave-In-Rock switchgrass managed for biomass production with three N rates and single end-of-season harvests

| N application, kg ha\(^{-1}\) | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|-----------------------------|------|------|------|------|------|------|------|
| 0 56 112                    | 0 56 112 | 0 56 112 | 0 56 112 | 0 56 112 | 0 56 112 | 0 56 112 | 0 56 112 |
| Land charge                 | – – – | 181 181 181 | 188 188 188 | 163 163 163 | 191 191 191 | 170 170 170 | 183 183 183 |
| Preharvest operating expense | – – – | 6 77 148 | 0 71 141 | 0 71 141 | 0 71 141 | 0 71 141 | 0 71 141 |
| Interest on operating expense | – – – | 0 2 4 | 0 2 4 | 0 2 4 | 0 2 4 | 0 2 4 | 0 2 4 |
| Machinery, equipment, labor | – – – | 18 32 32 | 0 13 13 | 0 13 13 | 0 13 13 | 0 13 13 | 0 13 13 |
| Harvesting                  | – – – | 273 257 273 | 241 273 257 | 241 305 305 | 257 336 368 | 162 226 273 | 241 305 352 |
| Establishment cost (prorated over 11 years @8%) | – – – | 48 48 48 | 48 48 48 | 48 48 48 | 48 48 48 | 48 48 48 |
| Total cost                  | – – – | 526 596 685 | 478 595 652 | 453 602 674 | 496 661 765 | 380 529 649 | 472 622 742 |
| Mean yield (Mg, 0% dm)       | – – – | 7.6 7.3 8.0 | 7.0 8.0 7.7 | 6.7 8.7 9.0 | 7.3 9.9 11.1 | 4.1 6.0 7.8 | 6.5 9.0 10.5 |
| Total cost ($ Mg\(^{-1}\))   | – – – | 7.0 8.2 8.6 | 6.9 7.4 8.5 | 6.8 6.9 7.5 | 6.8 6.7 6.9 | 9.2 8.8 8.4 | 7.3 6.9 7.1 |

*All costs in 2015 US dollars ($).
†$ ha\(^{-1}\) unless otherwise noted.
Table 7  New York annual production costs*† for Cave-In-Rock switchgrass managed for biomass production with three N rates and single end-of-season harvests

| N Application, kg ha⁻¹ | 2009   | 2010   | 2011   | 2012   | 2013   | 2014   | 2015   |
|------------------------|--------|--------|--------|--------|--------|--------|--------|
| 0                      | 56     | 112    | 0      | 56     | 112    | 0      | 56     |
| 2009                   | 85     | 85     | 85     | 78     | 78     | 89     |
| 2010                   | 74     | 147    | 0      | 74     | 147    | 0      |
| 2011                   | 13      | 13     | 0      | 13     | 13     | 0      |
| 2012                   | 114    | 114    | 114    | 85     | 85     | 89     |
| 2013                   | 147    | 147    | 0      | 74     | 147    | 0      |
| 2014                   | 0      | 74     | 147    | 0      |
| 2015                   | 78     |

| Land charge            | 98     | 98     | 98     | 114    | 114    | 89     | 89     |
| Preharvest operating   | 94     | 168    | 241    | 0      | 74     | 147    | 0      |
| interest on operating  | 3      | 5      | 6      | 0      | 2      | 4      | 0      |
| expense                | 94     | 168    | 241    | 0      | 74     | 147    | 0      |
| Machinery, equipment,  | 114    | 127    | 127    | 0      | 13     | 13     | 0      |
| labor                  | 13     | 13     | 0      | 13     | 13     | 0      |
| Harvesting             | 260    | 260    | 276    | 257    | 241    | 226    |
| Establishment cost     | 64     | 64     | 64     | 64     | 64     | 64     |
| (prorated over 11 years @8%) | 64     | 64     | 64     | 64     | 64     |
| Total cost             | 634    | 723    | 814    | 435    | 508    | 568    |
| Mean yield (Mg, 0% dm) | 6.7    | 6.6    | 6.9    | 7.3    | 6.7    | 6.2    |
| Total cost ($ Mg⁻¹)    | 94     | 109    | 117    | 60     | 76     | 92     |

*All costs in 2015 US dollars ($).
†$ ha⁻¹ unless otherwise noted.
Table 8  Oklahoma annual production costs*† for Blackwell switchgrass managed for biomass production with three N rates and single end-of-season harvests

| Nitrogen application, kg ha⁻¹ | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|-----------------------------|------|------|------|------|------|------|------|
|                             | 0    | 56   | 112  | 0    | 56   | 112  | 0    | 56   | 112  | 0    | 56   | 112  | 0    | 56   | 112  | 0    | 56   | 112  |
| Land charge                 | 60   | 60   | 60   | 72   | 72   | 72   | 55   | 55   | 55   | 51   | 51   | 51   | 44   | 44   | 44   | 47   | 47   | 47   |
| Preharvest operating expense| 78   | 145  | 212  | 78   | 146  | 213  | 0    | 67   | 134  | 0    | 67   | 134  | 0    | 67   | 134  | 0    | 67   | 134  |
| Interest on operating expense| 2    | 4    | 5    | 2    | 4    | 5    | 0    | 2    | 3    | 0    | 2    | 3    | 0    | 2    | 4    | 0    | 2    | 4    |
| Machinery, equipment, labor | 36   | 50   | 50   | 54   | 68   | 68   | 0    | 13   | 13   | 0    | 13   | 13   | 0    | 13   | 13   | 0    | 13   | 13   |
| Harvesting                  | 95   | 95   | 127  | 143  | 158  | 143  | 222  | 190  | 222  | 238  | 269  | 238  | 269  | 269  | 253  | 238  | 222  | 206  | 174  |
| Establishment cost (prorated over 11 years @8%) | 51   | 51   | 51   | 51   | 51   | 51   | 51   | 51   | 51   | 51   | 51   | 51   | 51   | 51   | 51   | 51   | 51   | 51   |
| Total cost                  | 321  | 404  | 504  | 400  | 498  | 551  | 327  | 377  | 478  | 339  | 453  | 490  | 364  | 447  | 500  | 335  | 401  | 455  | 273  |
| Mean yield (Mg, 0% dm)      | 3.4  | 3.6  | 4.3  | 5.0  | 5.4  | 5.3  | 8.0  | 6.6  | 8.0  | 8.5  | 9.5  | 8.6  | 9.6  | 9.9  | 9.0  | 8.3  | 8.0  | 7.5  | 6.4  |
| Total cost ($ Mg⁻¹)         | 94   | 113  | 118  | 80   | 92   | 105  | 41   | 57   | 60   | 40   | 48   | 57   | 38   | 45   | 55   | 40   | 50   | 60   | 43   |

*All costs in 2015 US dollars ($).
†$ ha⁻¹ unless otherwise noted.
Table 9  South Dakota annual production costs*† for Sunburst switchgrass managed for biomass production with three N rates and single end-of-season harvests

| Nitrogen application, kg ha⁻¹ | 2009  | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  |
|-------------------------------|-------|-------|-------|-------|-------|-------|-------|
| 0                             | 0     | 56    | 112   | 0     | 56    | 112   | 0     | 56    | 112   | 0     | 56    | 112   | 0     | 56    | 112   |
| Land charge                   | 137   | 137   | 117   | 117   | 108   | 108   | 105   | 105   | 105   | 117   | 117   | 117   | 118   | 118   | 118   | 105   | 105   | 105   |
| Preharvest operating expense  | 157   | 225   | 292   | 55    | 122   | 189   | 65    | 132   | 199   | 0     | 67    | 134   | 0     | 67    | 134   | 0     | 67    | 134   |
| Interest on operating expense | 1     | 3     | 5     | 1     | 3     | 5     | 0     | 2     | 4     | 0     | 2     | 4     | 0     | 2     | 4     | 0     | 2     | 4     |
| Machinery, equipment, labor   | 60    | 74    | 74    | 19    | 32    | 32    | 38    | 52    | 52    | 0     | 13    | 13    | 0     | 13    | 13    | 0     | 13    | 13    |
| Harvesting                    | 48    | 79    | 79    | 111   | 158   | 143   | 95    | 127   | 143   | 111   | 158   | 158   | 95    | 143   | 158   | 79    | 143   | 143   |
| Establishment cost (prorated over 11 years @8%) | 26    | 26    | 26    | 26    | 26    | 26    | 26    | 26    | 26    | 26    | 26    | 26    | 26    | 26    | 26    | 26    | 26    | 26    |
| Total cost                    | 430   | 543   | 612   | 329   | 459   | 512   | 332   | 446   | 531   | 242   | 372   | 441   | 238   | 368   | 453   | 224   | 369   | 438   |
| Mean yield (Mg, 0% dm)        | 2.0   | 2.7   | 3.1   | 3.9   | 5.4   | 5.2   | 3.6   | 4.8   | 5.0   | 3.8   | 5.4   | 5.9   | 3.3   | 5.0   | 5.9   | 3.1   | 5.1   | 5.4   |
| Total cost ($ Mg⁻¹)           | 217   | 202   | 196   | 84    | 85    | 98    | 93    | 93    | 106   | 64    | 68    | 75    | 72    | 74    | 77    | 73    | 73    | 82    |

*All costs in 2015 US dollars ($).
†$ ha⁻¹ unless otherwise noted.
Table 10  Virginia annual production costs*† for Alamo switchgrass managed for biomass production with three N rates and single end-of-season harvests

| N Application, kg ha\(^{-1}\) | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|-------------------------------|------|------|------|------|------|------|------|
| 0                             | 56   | 112  | 0    | 56   | 112  | 0    | 56   |
| 2009                          | 0    | 56   | 112  | 0    | 56   | 112  | 0    |
| 2010                          | 74   | 74   | 74   | 79   | 79   | 67   | 67   |
| 2011                          | 67   | 67   | 67   | 70   | 70   | 84   | 84   |
| 2012                          | 2013 | 74   | 147  | 0    | 74   | 147  | 0    |
| 74                            | 147  | 0    | 74   | 147  | 0    | 74   |
| 2014                          | 67   | 67   | 67   | 70   | 70   | 84   | 84   |
| 2015                          | 67   | 67   | 67   | 81   | 81   | 81   | 67   |

*All costs in 2015 US dollars ($).  
†$ ha\(^{-1}\) unless otherwise noted.
fields of uneven terrain’ (J. Cundiff, personal communication).

Although climate, soil drainage class, switchgrass ecotype, initial stand establishment, and N source all impacted switchgrass yields at the five sites, some across-site observations can be noted (Table 1). The two sites with good soil drainage (Virginia and South Dakota) had the lowest initial plant stands, showed yields increase over the first 3 years (a typical period for establishment), and demonstrated significant yield increases with N application. The combination of dry conditions, good soil drainage, and late planting date in Virginia likely combined to limit seedling establishment in the planting year. Sites with poor soil drainage (Iowa, New York, and Oklahoma) had good initial plant stands, but with little or no yield increase from the first to second crop year (yields were not measured in the establishment year). This observation points to the importance of the establishment year and of having as many seeds germinate and seedlings survive as possible. Well-drained fields may have been more susceptible to seedlings dying from moisture stress, which is an important factor affecting stand density (Hsu & Nelson, 1986). Therefore, well-drained sites are likely more sensitive to planting prior to extended dry periods, so planting dates should be selected that provide the greatest likelihood of regular precipitation to promote rapid establishment. It appears that if the initial stand is sufficient (and thus plant and tiller density are high), then adding N does not increase yields in the current year. On fields with low plant and tiller density, added N may improve yields. At one location in Texas, Muir et al. (2001) reported tiller mass of the lowland switchgrass Alamo increased with increasing N fertility.

The limited response to N inputs generally observed here is characteristic of switchgrass, particularly under single, end-of-season harvest management. Indeed, this has been an important criterion for choosing switchgrass as a potential energy crop. Several factors may contribute to this apparent lack of response, including an ability to mobilize large quantities of N from belowground storage (Lemus et al., 2008b; Dohleman et al., 2012; Wayman et al., 2014) and capacity to obtain large amounts of N from soil pools (Stout et al., 1991). In addition, N from atmospheric deposition (Coulston et al., 2004) and contributions of N from fungal and bacterial symbionts also may affect shoot N uptake and increase biomass production (Ghimire & Craven, 2011; Ker et al., 2012; Schroeder-Moreno et al., 2012).

Production costs and economics of N fertilization

Switchgrass yields on these marginal sites are generally well below those reported elsewhere. Jain et al. (2011) predicted peak yields in the Midwest ranging from 9.9 Mg ha⁻¹ (Minnesota) to 15.5 Mg ha⁻¹. In contrast, mean yields obtained here at the highest N rate range from 4.6 Mg ha⁻¹ (South Dakota) to 8.6 Mg ha⁻¹ (Virginia). Quite apart from N response, switchgrass yield of currently available cultivars on such marginal sites may not be sufficient to warrant establishment for purposes of supplying a biofuel or bioenergy facility, given the increased per-unit logistics costs associated with low yields or limited land base available (Fike et al., 2007). The cultivars used in the current study were all released between 1944 (Blackwell) and 1998 (Sunburst) and do not represent yield gains made in cultivars such as ‘Liberty’ (Vogel et al., 2014) released specifically for bioenergy. Gains in switchgrass biomass yield of up to 4% per year have been achieved through intrapopulation improvement methods (Casler & Vogel, 2014). More genetically improved cultivars are needed to significantly reduce the land base needed for a bioenergy facility. Using the estimated ethanol efficiency reported by Schmer et al. (2008) of 0.38 L kg⁻¹, a relatively small 100 mL yr⁻¹ ethanol refining facility would require from 31 000 ha (Virginia) to 57 000 ha (South Dakota) of similar farmland for sufficient switchgrass supply. Even though the switchgrass production costs estimated here are not encouraging for cellulosic ethanol production with current conversion rates, further inquiries into biomass production costs are likely warranted as new cultivars and other means of reducing unit production costs, logistics costs, and conversion rates are developed.

The key questions to be explored in the data from these sites is whether there is economic justification for application of N fertilizer, and if so, how much? As noted in the discussion of yields, observed evidence of yield response to N fertilization was relatively weak and sporadic, and in one site (New York), the yield response to N was sporadically negative. The economically efficient management rule is to increase input use until the value of production from the marginal input equals the price of that input (including application cost), or in other words, until marginal revenue equals marginal cost. The results for New York and Oklahoma (poorly drained sites) are clear – there is little or no apparent economic justification for any N application on these sites at any currently expected switchgrass price. In South Dakota, there was evidence of increased yields ($P < 0.05$) from application of 56 (or more) kg N ha⁻¹. However, the breakeven switchgrass price to justify such an application would need to be over $70 Mg⁻¹. In Virginia, significant yield increases resulted from N applications of 112 kg ha⁻¹. While there is some economic evidence to warrant such N application rates at switchgrass prices above $63 Mg⁻¹,
it is unclear whether the current bioenergy industry could support such a price, either for ethanol production or as part of a cogeneration energy production system.

The production costs and associated switchgrass yields reported here indicate the need for further production economic research of N response on marginal sites. Based on these results, typically promoted agronomic recommendations for such site conditions include costly and economically unjustified N application rates. Typical recommendations for N fertilization in published switchgrass budgets often range from 56 to 112 kg ha\(^{-1}\). At N prices used here, such applications add $37–$74 ha\(^{-1}\) to production costs, with sparse evidence of an economically profitable response of the currently available cultivars.

Conclusions

Switchgrass production has received little exploration in field-scale settings using the complement of typical establishment and harvest systems. When grown and harvested for biomass on marginal lands, switchgrass yields will be less than typically reported in small-plot studies. Under the end-of-season harvest management system utilized here, response to N is often limited. Thus, while the general recommendation has been to fertilize the crop to meet replacement needs, this research suggests that generalized N fertilizer recommendations will not be sufficient to provide optimum fertility management across multiple agro-ecoregions.

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