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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

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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

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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 nonmarginal 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 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.*, 2008b; 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 × 0.75-m metal grid following Vogel & Masters (2001). Briefly, each grid contained 25 15-cm × 15-cm cells, and the sum of cells in which switchgrass was counted as present (from the four

Table 1 Sites and soils used in a long-term field-scale switchgrass production study

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 Fragiaquepts	0.39
		Langford	Fine-loamy, mixed, active, mesic Typic Fragiudepts	
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.

readings) was used to estimate stand percent for each plot at the start of the 2009 growing season (Table 5). Yield data for this study cover the 2009–2015 crop years (Table 5). In South Dakota, yields were determined by mowing and baling a strip through the middle of each plot (approximately 5.5 m wide and 300 m long) with standard agricultural equipment available on the farm. At the remaining sites, all bales from each experimental field were weighed and the biomass yields were calculated as total bale weight per plot × percent dry matter of the plot subsample. At each site, switchgrass subsamples (approximately 2 kg) from each plot were collected by hand from within the row (prior to baling), or from the yield strip cut with the plot harvester (South Dakota). Across sites, switchgrass subsamples were weighed and then dried at 55 °C for a minimum of 48 h and then reweighed for moisture determination. Based on common experience and agreement among team members, a correction factor of 0.92 was applied to all dry matter values to adjust yields to an estimated 0% moisture basis.

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 PDMIXX 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 Miranowski *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

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

	Yearly total precipitation, mm								Average daily temperature, °C							
	Year							30-year	Year							30-year
State (county)	2009	2010	2011	2012	2013	2014	2015	Mean*	2009	2010	2011	2012	2013	2014	2015	Mean*
Iowa (Story)	–								–							
New York (Tompkins)	848	980	1301	834	991	978	858	937	7.5	8.7	8.8	9.6	8.0	7.0	7.7	8.1
Oklahoma (Muskogee)	1079	848	971	659	1103	983	1956	1137	14.8	15.3	16.0	17.3	14.6	14.4	15.4	15.5
South Dakota (Day)	716	677	538	585	617	432	499	619	5.1	6.8	6.2	8.3	4.9	4.9	7.9	6.4
Virginia (Pittsylvania)	1424	1215	1074	1011	1391	1173	1363	1144	12.5	12.9	13.4	13.5	12.0	11.3	12.9	12.8

*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 × site, year × treatment, and site × 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.

Iowa. Yields were significantly affected ($P < 0.0001$) by year, treatment, and year × treatment interaction ($P < 0.0009$). In the first crop year, yields were not affected by N application. Responses to N were

Table 3 Land management practices by site for establishing switchgrass for a long-term field-scale switchgrass production study

State	Previous crop*	Vegetation treatment	Land preparation	Cultivar†	Planting date	At-/postplant herbicide
Iowa	Maize/soybean rotation	None	Planted with maize	Cave-in-Rock	May 8, 2009	Imazethapyr, 280 g ha^{-1}; Atrazine, 1.1 kg ha^{-1}
New York	Cool season grass hay	Glyphosate, 3.5 L ha^{-1}	Plow, disk, cultivate	Cave-in-Rock	May 29, 2008	Halosulfuron, 47 g ha^{-1}
Oklahoma	Warm season grass pasture	Glyphosate 2.3 L ha^{-1}	None (no-till planting)	Blackwell	September 2, 2008	None
South Dakota	Soybean	None	None (no-till planting)	Sunburst	May 17, 2008	Quinclorac, 346 g ha^{-1} Atrazine, 2.34 L ha^{-1} Bromoxynil octanoate, 0.58 L ha^{-1}
Virginia	Cool season grass hay	Gramoxone 3.6 L ha^{-1}; burn dead vegetation	None (no-till planting)	Alamo	July 1, 2008	Quinclorac, 560 g ha^{-1} 2,4-D, 1.2 L ha^{-1}

*Soybean = *Glycine max*; Tall fescue = *Festuca arundinacea* syn *Lolium arundinaceum*.

†A standard seeding rate (8.9 kg ha^{-1} pure live seed) was planted using a no-till drill at each site.

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	2.3 L ha^{-1}	Ammonium sulfate	Mow + rake	Square
		Dicamba	1.2 L ha^{-1}			
Oklahoma	2009	Quinclorac	370 g ha^{-1}	Urea	Mow + rake	Round
		2,4-DB	3.5 L ha^{-1}			
	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 + fluroxypyr 1 methylheptyl ester	1.2 L ha^{-1}	Urea	Mow	Round
		Quinclorac	350 g ha^{-1}			
		Atrazine	2.3 L ha^{-1}			
		Dicamba	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	1.6 L ha^{-1}			
		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	4.7 L ha^{-1}	Ammonium sulfate	Mow + rake	Round
		2,4-D	1.2 L ha^{-1}			
		Quinclorac	560 g ha^{-1}			

*Years designate times for herbicide applications only. Nitrogen source, harvest practices, and baler 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.

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

State (locality)	Year	Stand, %	Yield, Mg ha^{-1}*			
			Nitrogen application, kg ha^{-1}			
			0	56	112	SE
Iowa (Ames)	2009		–	–	–	–
	2010	75.9	6.96	6.73	7.35	0.377
	2011		6.41b	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	5.71c	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		6.93a	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 (Madakadze *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.

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
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	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})	–	–	–	70	82	86	69	74	85	68	69	75	68	67	69	92	88	84	73	69	71

*All costs in 2015 US dollars ($).

†$ ha^{-1} unless otherwise noted.

Oklahoma. Blackwell switchgrass yields in this study were about three to fourths 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; Kering *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.

Virginia. As with South Dakota, large (92%) yield gains occurred from crop year 2009 to 2010 (3.56–6.85 Mg ha^{-1}) in Virginia, which had the lowest initial switchgrass stand percentage (27.8%) among sites. Biomass yields at this site were substantially lower than those from regional studies in the upper southeastern USA (Fike *et al.*, 2006a,b). In those studies, Alamo switchgrass receiving 50 or 100 kg N ha^{-1} produced about 15 Mg ha^{-1} yr^{-1} with one annual harvest. The Virginia site was the most responsive to added N fertility and likely reflects the fact that the Virginia site had more marginal soil with lowest soil N to depth (Owens *et al.*, 2013). 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 'small, irregularly shaped

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	112	0	56	112	0	56	112	0	56	112	0	56	112
Land charge	98	98	98	114	114	114	85	85	85	78	78	78	89	89	89	85	85	85	82	82	82
Preharvest operating expense	94	168	241	0	74	147	0	74	147	0	74	147	0	74	147	0	74	147	0	74	147
Interest on operating expense	3	5	6	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4
Machinery, equipment, labor	114	127	127	0	13	13	0	13	13	0	13	13	0	13	13	0	13	13	0	13	13
Harvesting	260	260	276	257	241	226	289	241	257	257	273	257	336	321	321	273	241	241	273	257	257
Establishment cost (prorated over 11 years @8%)	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64
Total cost	634	723	814	435	508	568	438	479	571	399	504	564	490	563	638	422	480	555	419	492	568
Mean yield (Mg, 0% dm)	6.7	6.6	6.9	7.3	6.7	6.2	8.5	6.6	7.4	7.2	7.6	7.3	10.2	9.6	9.3	7.6	6.8	6.5	7.5	7.0	7.2
Total cost ($ Mg^{-1})	94	109	117	60	76	92	52	72	77	55	67	77	48	59	68	55	70	85	56	71	78

*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	0	56	112
Land charge	60	60	60	72	72	72	55	55	55	51	51	51	44	44	44	47	47	47	48	48	48
Preharvest operating expense	78	145	212	78	146	213	0	67	134	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	0	2	4
Machinery, equipment, labor	36	50	50	54	68	68	0	13	13	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	222	190
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	51	51	51
Total cost	321	404	504	400	498	551	327	377	478	339	453	490	364	447	500	335	401	455	273	403	440
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	7.8	6.6
Total cost (\$ Mg^{-1})	94	113	118	80	92	105	41	57	60	40	48	57	38	45	55	40	50	60	43	52	67

*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	56	112	0	56	112	0	56	112	0	56	112	0	56	112	0	56	112	0	56	112
Land charge	137	137	137	117	117	117	108	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	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	0	2	4
Machinery, equipment, labor	60	74	74	19	32	32	38	52	52	0	13	13	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	79	111	127
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	26	26	26
Total cost	430	543	612	329	459	512	332	446	531	242	372	441	238	368	453	224	369	438	210	324	409
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	2.8	4.0	4.7
Total cost (\$ Mg^{-1})	217	202	196	84	85	98	93	93	106	64	68	75	72	74	77	73	73	82	76	80	88

*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	112	0	56	112	0	56	112	0	56	112	0	56	112
Land charge	74	74	74	79	79	79	67	67	67	70	70	70	84	84	84	81	81	81	67	67	67
Preharvest operating expense	124	198	272	0	74	147	0	74	147	0	74	147	0	74	147	0	74	147	0	74	147
Interest on operating expense	3	4	6	0	2	3	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4
Machinery, equipment, labor	54	68	68	0	13	13	0	13	13	0	13	13	0	13	13	0	13	13	0	13	13
Harvesting	130	162	178	194	257	321	194	241	305	226	305	368	178	257	305	273	321	352	257	257	273
Establishment cost (prorated over 11 years @8%)	52	52	52	52	52	52	52	52	52	52	52	52	52	52	52	52	52	52	52	52	52
Total cost	438	558	650	325	477	616	312	449	588	347	515	655	314	482	605	406	543	650	376	465	556
Mean yield (Mg, 0% dm)	3.0	4.1	4.5	5.2	7.2	9.8	5.1	6.9	9.2	6.1	9.1	11.4	4.6	7.4	9.1	8.1	9.6	10.9	7.2	7.4	8.0
Total cost ($ Mg^{-1})	148	135	145	62	66	63	61	65	64	57	57	57	68	66	67	50	56	60	52	63	70

*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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References

Adler PR, Sanderson MA, Boateng AA, Weimer PJ, Jung HJG (2006) Biomass yield and biofuel quality of switchgrass harvested in fall or spring. *Agronomy Journal*, **98**, 1518–1525.

Aravindhakshan SC, Epplin FM, Taliaferro CM (2011) Switchgrass, Bermudagrass, Flaccidgrass, and Lovegrass biomass yield response to nitrogen for single and double harvest. *Biomass and Bioenergy*, **35**, 308–319.

Bhardwaj AK, ZenoneT Jasrotia P, Robertson GP, Chen J, Hamilton SK (2011) Water and energy footprints of bioenergy crop production on marginal lands. *GCB Bioenergy*, **3**, 208–222.

Bow JR, Muir JP (2010) Dynamics of harvesting and feeding Cynodon hybrid tifton 85 hay of varying maturities to wether kids. *Small Ruminant Research*, **93**, 198–201.

Boyer DN, Tyler DD, Roberts RK, English BC, Larson JA (2012) Switchgrass yield response functions and profit-maximizing nitrogen rates on four landscapes in Tennessee. *Agronomy Journal*, **104**, 1579–1588.

Cai X, Zhang X, Wang D (2011) Land availability for biofuel production. *Environmental Science & Technology*, **45**, 334–339.

Casler MD, Vogel KP (2014) Selection for biomass yield in upland, lowland, and hybrid switchgrass. *Crop Science*, **54**, 626–636.

Coble CG (1989) Harvesting strategies for high yielding biomass crops. *Energy from Biomass and Wastes XII*, pp. 361–377. Institute of Gas Technology, Chicago, IL.

Coulston JW, Riitters KH, Smith GC (2004) A preliminary assessment of the Montreal process indicators of air pollution for the United States. *Environmental Monitoring and Assessment*, **95**, 57–74.

Cundiff JS, Fike JH, Parrish DJ, Alwang J (2009) Logistic constraints in developing dedicated large-scale bioenergy systems in the Southeastern United States. *Journal of Environmental Engineering*, **135**, 1086–1096.

Dohleman FG, Heaton EA, Arundale RA, Long SP (2012) Seasonal dynamics of above- and below-ground biomass and nitrogen partitioning in *Miscanthus 3 giganteus* and *Panicum virgatum* across three growing seasons. *GCB Bioenergy*, **4**, 534–544.

Edwards WM, Johanns AM (2012) 2012 Iowa farm custom rate survey. Ag Decision Maker. File A3-10. 5 pp. Available at: http://www.extension.iastate.edu/buchanan/sites/www.extension.iastate.edu/files/buchanan/Farm%20Custom%20Rate%20Survey.pdf (accessed 01 December 2016).

Fike JH, Parrish DJ, Wolf DD, Balasko JA, Green JT Jr, Rasnake M, Reynolds JH (2006a) Long-term yield potential of switchgrass-for-biofuel systems. *Biomass and Bioenergy*, **30**, 198–206.

Fike JH, Parrish DJ, Wolf DD, Balasko JA, Green JT Jr, Rasnake M, Reynolds JH (2006b) Switchgrass production for the upper southeastern USA: influence of cultivar and cutting frequency on biomass yields. *Biomass and Bioenergy*, **30**, 207–213.

Fike JH, Parrish DJ, Alwang J, Cundiff JS (2007) Challenges for deploying dedicated, large-scale, bioenergy systems in the USA. *CAB Reviews*, **2**, 28.

Fike JH, Butler TJ, Mitchell R (2014) Agronomy of switchgrass for biomass production. In: *Compendium of Bioenergy Plants: Switchgrass* (eds Luo H, Wu Y), pp. 16–66, 464. CRC Press, Boca Raton, FL.

Foster JL, Guretzky JA, Huo C, Kering MK, Butler TJ (2012) Effects of row spacing, seeding rates, and planting date on establishment and biomass of switchgrass. *Crop Science*, **53**, 309–314.

Gelfand I, Sahajpal R, Zhang XS, Izaurralde RC, Gross KL, Robertson GP (2013) Sustainable bioenergy production from marginal lands in the US Midwest. *Nature*, **493**, 514–517.

Ghimire SR, Craven KD (2011) Enhancement of switchgrass (*Panicum virgatum* L.) biomass production under drought conditions by the ectomycorrhizal fungus *Sebacina vermifera*. *Applied and Environmental Microbiology*, **77**, 7063–7067.

Gopalakrishnan G, Negri MC, Snyder SW (2011) A novel framework to classify marginal land for sustainable biomass feedstock production. *Journal of Environmental Quality*, **40**, 1593–1600.

Guretzky JA, Biermacher JT, Cook BJ, Kering MK, Mosali J (2011) Switchgrass for forage and bioenergy: harvest and nitrogen rate effects on biomass yields and nutrient composition. *Plant and Soil*, **339**, 69–81.

Hall CAS, Dale BE, Pimentel D (2011) Seeking to understand the reasons for different energy return on investment (EROI) estimates for biofuels. *Sustainability*, **3**, 2413–2432.

Hartman JC, Nippert JB, Orozco RA, Springer CJ (2011) Potential ecological impacts of switchgrass (*Panicum virgatum* L.) biofuel cultivation in the Central Great Plains, USA. *Biomass and Bioenergy*, **35**, 3415–3421.

Heggenstaller AH, Moore KJ, Liebman M, Anex RP (2009) Nitrogen influences biomass and nutrient partitioning by perennial, warm-season grasses. *Agronomy Journal*, **101**, 1363–1371.

Hill J, Nelson E, Tilman D, Polasky S, Tiffany D (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences of the United States of America*, **103**, 11206–11210.

Hintz RL, Harmoney KR, Moore KJ, George JR, Brummer EC (1998) Establishment of switchgrass and big bluestem in corn with atrazine. *Agronomy Journal*, **90**, 591–596.

Hong CO, Owens VN, Bransby D *et al.* (2014) Switchgrass response to nitrogen fertilizer across diverse environments in the USA: a Regional Feedstock Partnership report. *BioEnergy Research*, **7**, 777–788.

Hsu FH, Nelson CJ (1986) Planting date effects on seedling development of perennial warm- season forage grasses. II. Seedling growth. *Agronomy Journal*, **78**, 38–42.

Jain AK, Khanna M, Erickson M, Huang HX (2010) An integrated biogeochemical and economic analysis of bioenergy crops in the Midwestern United States. *GCB Bioenergy*, **2**, 217–234.

Ker K, Seguin P, Driscoll BT, Fyles JW, Smith DL (2012) Switchgrass establishment and seeding year production can be improved by inoculation with rhizosphere endophytes. *Biomass and Bioenergy*, **47**, 295–301.

Kering MK, Biermacher JT, Butler TJ, Mosali J, Guretzky JA (2012a) Biomass yield and nutrient responses of switchgrass to phosphorus application. *BioEnergy Research*, **5**, 71–78.

Kering MK, Butler TJ, Biermacher JT, Guretzky JA (2012b) Biomass yield and nutrient removal rates of perennial grasses under nitrogen fertilization. *BioEnergy Research*, **5**, 61–70.

Lazarus WF (2016) Machinery cost estimates. University of Minnesota Extension, Minneapolis, MN. Available at: http://wlazarus.cfans.umn.edu/william-f-lazarus-farm-machinery-management (accessed 15 July 2016).

Lee DK, Owens VN, Doolittle JJ (2007) Switchgrass and soil carbon sequestration response to ammonium nitrate, manure, and harvest frequency on conservation reserve program land. *Agronomy Journal*, **99**, 462–468.

Lee DK, Owens VN, Boe A, Koo B (2009) Biomass and seed yields of big bluestem, switchgrass, and intermediate wheatgrass in response to manure and harvest timing at two topographic positions. *GCB Bioenergy*, **1**, 171–179.

Lemus R, Brummer EC, Moore KJ, Molstad NE, Burras CL, Barker MF (2002) Biomass yield and quality of 20 switchgrass populations in southern Iowa, USA. *Biomass and Bioenergy*, **23**, 433–442.

Lemus R, Brummer EC, Burras CL, Moore KJ, Barker MF, Molstad NE (2008a) Effects of nitrogen fertilization on biomass yield and quality in large fields of established switchgrass in southern Iowa, USA. *Biomass and Bioenergy*, **32**, 1187–1194.

Lemus R, Parrish DJ, Abaye O (2008b) Nitrogen-use dynamics in switchgrass grown for biomass. *BioEnergy Research*, **1**, 153–162.

Liebig MA, Morgan JA, Reeder JD, Ellert BH, Gollany HT, Schuman GE (2005) Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. *Soil & Tillage Research*, **83**, 25–52.

Liu X-JA, Fike JH, Galbraith JM, Fike WB, Parrish DJ, Evanylo GK, Strahm BD (2013) Effects of harvest frequency and biosolids application on switchgrass yield, feedstock quality, and theoretical ethanol yield. *GCB Bioenergy*, **7**, 112–121.

Liu X-JA, Fike JH, Galbraith JM, Fike WB (2014) Switchgrass response to cutting frequency and biosolids amendment: biomass yield, feedstock quality, and theoretical ethanol yield. *BioEnergy Research*, **7**, 1191–1200.

Lötjönen T (2008) Harvest losses and bale density in reed canary grass (*Phalaris arundinacea* L.) spring-harvest. *Aspects of Applied Biology*, **90**, 263–268.

Ma Z, Wood CW, Bransby DI (2001) Impact of row spacing, nitrogen rate, and time on carbon partitioning of switchgrass. *Biomass and Bioenergy*, **20**, 413–419.

Madakadze IC, Stewart K, Peterson PR, Coulman BE, Smith DL (1999a) Switchgrass biomass and chemical composition for biofuel in Eastern Canada. *Agronomy Journal*, **91**, 696–701.

Madakadze IC, Stewart K, Peterson PR, Coulman BE, Smith DL (1999b) Cutting frequency and nitrogen fertilization effects on yield and nitrogen concentration of switchgrass in a short season area. *Crop Science*, **39**, 552–557.

Makaju SO, Wu YQ, Zhang H, Kakani VG, Taliaferro CM, Anderson MP (2013) Switchgrass winter yield, year-round elemental concentrations, and associated soil nutrients in a zero input environment. *Agronomy Journal*, **105**, 463–470.

Maung TA, Gustafson CR (2013) Economic impact of harvesting corn stover under time constraint: the case of North Dakota. *Economics Research International*, **2013**, Article ID 321051.

McKenna JR, Wolf DD (1990) No-till switchgrass establishment as affected by limestone, phosphorus, and carbofuran. *Journal of Production Agriculture*, **3**, 475–479.

McLaughlin SB, Kszos LA (2005) Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. *Biomass and Bioenergy*, **28**, 515–535.

Meehan PG, McDonnell KP, Finnan JM (2013) An assessment of the effect of harvest time and harvest method on biomass loss for *Miscanthus × giganteus*. *GCB Bioenergy*, **5**, 400–407.

Miranowski J, Khanna M, Hess JR (2010) Economics of feedstock production, harvest, storage, and transport. In: *Sustainable Feedstocks for Advanced Biofuels Workshop* (eds Braun R, Karlen D, Johnson D), pp. 177–192. Soil and Water Conservation Society, Atlanta, GA.

Mitchell RB, Vogel KP (2012) Germination and emergence tests for predicting switchgrass field establishment. *Agronomy Journal*, **104**, 458–465.

Mitchell RB, Vogel KP, Berdahl J, Masters RA (2010) Herbicides for establishing switchgrass in the Central and Northern Great Plains. *BioEnergy Research*, **3**, 321–327.

Mitchell RB, Vogel KP, Schmer MR (2013) *Switchgrass (Panicum virgatum) for biofuel production*. Sustainable Ag Energy Community of Practice, eXtension. Available at: https://articles.extension.org/pages/26635/switchgrass-panicum- virgatum-for- biofuel-production (accessed 01 December 2016).

Mooney DF, Roberts RK, English BC, Tyler DD, Larson JA (2009) Yield and breakeven price of 'Alamo' switchgrass for biofuels in Tennessee. *Agronomy Journal*, **101**, 1234–1242.

Muir JP, Sanderson MA, Ocumpaugh WR, Jones RM, Reed RL (2001) Biomass production of 'Alamo' switchgrass in response to nitrogen, phosphorus, and row spacing. *Agronomy Journal*, **93**, 896–901.

Mulkey VR, Owens VN, Lee DK (2006) Management of switchgrass-dominated conservation reserve program lands for biomass production in South Dakota. *Crop Science*, **46**, 712–720.

Mulkey VR, Owens VN, Lee DK (2008) Management of warm-season grass mixtures for biomass production in South Dakota USA. *Bioresource Technology*, **99**, 609–617.

Myhre MA (2010) *Farm Net Income Impact of Switchgrass Production and Corn Stover Collection for Heat and Power Generation*. University of Wisconsin, Science Gaylord Nelson Institute for Environmental Studies, Madison, WI.

Owens VN, Viands DR, Mayton HS *et al.* (2013) Nitrogen use in switchgrass grown for bioenergy across the USA. *Biomass and Bioenergy*, **58**, 286–293.

Parrish DJ, Fike JH (2005) The biology and agronomy of switchgrass for biofuels. *Critical Reviews in Plant Sciences*, **24**, 423–459.

Perrin R, Vogel K, Schmer M, Mitchell R (2008) Farm-scale production cost of switchgrass for biomass. *BioEnergy Research*, **1**, 91–97.

Rogers JK, Motal FJ, Mosali J (2012) Yield distribution, and forage quality of warm-season perennial grasses grown for pasture or biofuel in the Southern Great Plains. *ISRN Agronomy*, **2012**, Article ID 607476. https://doi.org/10.5402/2012/607476.

Sanderson MA, Reed RL (2000) Switchgrass growth and development: water, nitrogen, and plant density effects. *Journal of Range Management*, **53**, 221–227.

Saxton AM (1998) A macro for converting mean separation output to letter groupings in Proc Mixed. In: *23rd SAS Users Group Intl*, pp. 1243–1246. SAS Institute, Cary, NC.

Schmer MR, Vogel KP, Mitchell RB, Moser LE, Eskridge KM, Perrin RK (2006) Establishment stand thresholds for switchgrass grown as a bioenergy crop. *Crop Science*, **46**, 157–161.

Schmer MR, Vogel KP, Mitchell RB, Perrin RK (2008) Net energy of cellulosic ethanol from switchgrass. *Proceedings of the National Academy of Sciences of the United States of America*, **105**, 464–469.

Schroeder-Moreno MS, Greaver TL, Wang S, Hu S, Rufty TW (2012) Mycorrhizal-mediated nitrogen acquisition in switchgrass under elevated temperatures and N enrichment. *GCB Bioenergy*, **4**, 266–276.

Searchinger T, Heimlich R, Houghton RA *et al.* (2008) Use of U.S croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, 1238–1240.

Stout WL, Staley TE, Shaffer JA, Jung GA (1991) Quantitative effects of soil depth and soil and fertilizer nitrogen on nitrogen uptake by tall fescue and switchgrass. *Communications in Soil Science and Plant Analysis*, **22**, 1647–1660.

Teel A, Barnhart S, Miller G (2003) *Management Guide for the Production of Switchgrass for Biomass Fuel in Southern Iowa*. University Extension Publication PM-1710. Iowa State University, Ames, IA.

Thomason WE, Raun WR, Johnson GV, Taliaferro CM, Freeman KW, Wynn KJ, Mullen RW (2004) Switchgrass response to harvest frequency and time and rate of applied nitrogen. *Journal of Plant Nutrition*, **27**, 1199–1226.

USDA-NASS (National Agricultural Statistics Service) (2013a) Agricultural Prices. Available at: https://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1002 (accessed 3 June 2013).

USDA-NASS (National Agricultural Statistics Service) (2013b) Cash Rents by County. Available at: https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Cash_Rents_by_County/ (accessed 3 June 2013).

USDA-NASS (National Agricultural Statistics Service) (2013c) Quick Stats. Available at: https://www.nass.usda.gov/Quick_Stats/ (accessed 3 June 2013).

Venuto BC, Daniel JA (2010) Biomass feedstock harvest from conservation reserve program land in northwestern Oklahoma. *Crop Science*, **50**, 737–743.

Vogel KP, Masters RA (2001) Frequency grid – a simple tool for measuring grassland establishment. *Journal of Range Management*, **54**, 653–655.

Vogel KP, Brejda JJ, Walters DT, Buxton DR (2002) Switchgrass biomass production in the Midwest USA: harvest and nitrogen management. *Agronomy Journal*, **94**, 413–420.

Vogel KP, Mitchell RB, Casler MD, Sarath G (2014) Registration of 'Liberty' switchgrass. *Journal of Plant Registrations*, **8**, 242–247.

Wayman S, Bowden RD, Mitchell RB (2014) Seasonal changes in shoot and root nitrogen distribution in switchgrass (*Panicum virgatum*). *BioEnergy Research*, **7**, 243–252.

Wolf DD, Fiske DA (2009) *Planting and Managing Switchgrass for Forage, Wildlife, and Conservation*. Virginia Cooperative Extension Publication 418-013. Virginia Polytechnic Institute and State University, Blacksburg, VA.

Wright L (2007) *Historical Perspective on how and why Switchgrass was Selected as a "Model" High-Potential Energy Crop*. ORNL/TM-2007/109. Oak Ridge National Laboratory, Oak Ridge, TN.

Wright L, Turhollow A (2010) Switchgrass selection as a "model" bioenergy crop: a history of the process. *Biomass and Bioenergy*, **34**, 851–868.

Wullschleger SD, Davis EB, Borsuk ME, Gunderson CA, Lynd LR (2010) Biomass production in switchgrass across the United States: database description and determinants of yield. *Agronomy Journal*, **102**, 1158–1168.

Zhang J, Osmani A, Awudu I, Gonela V (2013) An integrated optimization model for switchgrass-based bioethanol supply chain. *Applied Energy*, **102**, 1205–1217.