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Effects of nitrogen fertilization on biomass yield and quality in large fields of established switchgrass in southern Iowa, USA☆

Roque Lemus[a], E. Charles Brummer[b,*], C. Lee Burras[c], Kenneth J. Moore[c], Michael F. Barker[c], Neil E. Molstad[d]

[a]Department of Agricultural Sciences, Texas A&M University, Commerce, TX 75429, USA
[b]Center for Applied Genetic Technologies, University of Georgia, Athens, GA 30602, USA
[c]Department of Agronomy, Iowa State University, Ames, IA 50011, USA
[d]USDA-NRCS Hawaii Resource Office, 101 Aupuni Street Suite 229, Hilo, HI 96720, USA

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ABSTRACT

Switchgrass (*Panicum virgatum* L.) is a potential biofuel crop in the midwestern United States. The objective of this experiment was to test the effect of nitrogen application on biomass dry matter yield and fiber and mineral concentrations in large field plots in Lucas and Wayne counties in southern Iowa. Two established switchgrass fields with a previous history of limited management were evaluated from 1998 through 2002. Nitrogen was applied in the spring at rates of 0, 56, 112, and 224 kg N ha^{-1}, and a single biomass harvest was made in autumn. Biomass production averaged across locations and N levels increased by 3.6 mg ha^{-1} between 1998 and 2002 to 6.5 mg ha^{-1}. Nitrogen improved yields, with the response declining as N levels increased. The highest yield throughout the experiment was 8.5 mg ha^{-1} at the Lucas location in 2002. Changes in fiber and mineral concentrations did not follow any trend over years but were likely due to differences in harvest date among years. Nitrogen fertilization had no meaningful effect on the quality of the biofuel produced. This study clearly shows that nitrogen application and proper agronomic management can substantially increase the yield of established switchgrass fields over time without affecting the quality of the feedstock. As this experiment was conducted in large plots using commercial farm machinery, the results should be broadly applicable to real world situations.

1. Introduction

The soils and landscapes of southern Iowa combine areas ideally suited for agronomic crop production with regions having severe cropping restrictions. The main production limitation arises from the prevalence of soil associations that are highly erosive, shallow to root restrictive zones, and/or excessively wet [1]. Switchgrass (*Panicum virgatum* L.), a native warm-season perennial grass, is adapted to the area and could function as one component in a multipurpose cropping system. Traditionally, switchgrass has been used for livestock feed, wildlife habitat, and cash hay.

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*Corresponding author. Tel.: +1 706 542 8847; fax: +1 706 583 8120.
E-mail address: brummer@uga.edu (E. Charles Brummer).

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Adding switchgrass to a row cropping operation could lead to major improvements in the sustainability of agroecosystems [2]. Experiments funded principally by the United States Department of Energy over the past two decades have shown that switchgrass is also a model herbaceous species for bioenergy production because of its perenniality, wide geographic distribution, high nutrient use efficiency, relatively low fertilization requirements, high biomass yield potential, and compatibility with conventional farm practices [2,3]. In order for switchgrass to be used to generate electricity by cofiring with coal, a substantial amount of biomass would need to be produced in the area close to the generating plant. A scale-up project funded by the Department of Energy in southern Iowa intends to grow several thousand hectares of switchgrass in the Lake Rathbun watershed, a region typified by the problematic soils described earlier.

Switchgrass has excellent qualities for energy use, but to reach its production potential, the timing and amount of fertilizer application and harvesting methods must be optimized to minimize dry matter loss and maximize biofuel quality [4]. Although biomass crops, such as switchgrass, can be planted and harvested like traditional forage crops, management strategies differ substantially between biomass and forage production, with the former primarily interested in total production, while the latter is also concerned with nutritive value.

The profitability of switchgrass as a biomass crop would be enhanced if acceptable yields were produced with a minimum amount of nitrogen [5]. Previous studies suggest that the annual nitrogen requirement of switchgrass is about half that required for maize (*Zea mays* L.) production, or between 70 and 100 kg ha^{-1} [3]. Optimizing the application of nitrogen spatially and temporally is important to reach desirable switchgrass biomass yields without jeopardizing water quality or economic returns in the process [4].

In addition to total biomass production, various attributes determine the suitability of energy crops for combustion or gasification. These include the total energy content in the cell wall fraction (cellulose, hemicellulose, and lignin), the chemical composition of ash produced during the combustion process, and the moisture content [6]. Most studies conducted on biomass quality simply report forage nutritive value, which while being useful, does not provide adequate information for use as a biofuel. In particular, the concentration of total ash, as well as alkali metals (Na, K, Mg, P, and Ca), chloride, nitrogen, and sulfur are important in assessing the affect burning the biofuel will have on life of the power plant infrastructure as well as on the emissions from the plant [6]. A switchgrass of ideal quality is one that has high lignin content and low ash, nitrogen, sulfur, and chloride concentrations.

Because we were interested in large-scale switchgrass production, we conducted an experiment evaluating biomass yield and quality on commercial sized plots that encompassed a diversity of topographies (in this case, a summit, backslope, and footslope within each plot) and in which all management operations could be completed using standard, full-size farm equipment. The results of this experiment reflect the diversity of soil types, slopes, aspects, and microclimates that farmers encounter, which are typically not present on research farms. Further, much switchgrass being grown in southern Iowa and surrounding regions that could potentially be used for bioenergy purposes is currently enrolled in the USDA Conservation Reserve Program (CRP). Land enrolled in the CRP is taken out of crop production, seeded to a perennial grass, and given minimum management for the length of the contract, typically 10 years. No commercial products can be harvested or sold from CRP land. Therefore, management of typical CRP fields is not optimum for agronomic production.

The objective of this experiment was to evaluate the biomass production and quality from large field plots of established switchgrass enrolled in the CRP program fertilized with four levels of nitrogen over a 5-year period. Our hypothesis was that nitrogen application would improve yields above unfertilized plots and that yields would increase within fertility treatments for at least several years simply because of better management. We anticipated nitrogen fertilization would have no detrimental effects on biofuel quality.

2. Materials and methods

2.1. *Field plot design*

The experiment was conducted on two farms in southern Iowa from 1998 through 2002. One location, in Lucas County, was located 15 km southwest of Chariton near Derby (40°55′N, 93°23′W); the other, in Wayne County, was 8 km southeast of Millerton (40°50′N, 93°15′W). At both locations, a 10-year-old stand of 'Cave-in-Rock' switchgrass, which had been enrolled in the CRP, was used for the experiment. These fields had a history of limited management prior to our use. The experimental design was a randomized complete block design with five replications at each location. The landscapes and soils are typical of the area with loess and Yarmouth-Sangamon paleosol being the most common parent materials. Small areas of till-derived soils are also present. The soils are almost entirely poorly or somewhat poorly drained Mollisols having high-clay argillic horizons (Table 1).

Each replication included four plots randomly assigned to nitrogen fertility treatments of 0, 56, 112, and 224 kg N ha^{-1}. Nitrogen was applied as urea ($CO(NH_2)_2$) on 4 June 1998 and as ammonium nitrate (NH_4NO_3) (30-0-0) on 26 June 1999, 31 May 2000, 12 July 2001, and 7 May 2002. An error by the commercial nitrogen applicator in 2001 resulted in the application of 0, 56, 112, or 224 kg NH_4NO_3 ha^{-1}. No other fertilizer was applied. Atrazine (2-chloro-4-ethylamino-6-isopropyl amino-s-atrazine) was applied at a rate of 2.24 kg active ingredient ha^{-1} on 6 June 1998 and 18 June 1999 for weed control. Prior to initiation of spring growth each year, standing dead material was mowed to a 6-cm stubble height and the residue removed. Plots were 15 m wide and between 60 and 140 m long at Lucas and 18 m wide and between 30 and 45 m long at Wayne. The length was varied to enable summit, backslope, and swale landscape positions to be included in each plot. The slopes within plots ranged from 1% to 13%. The plot size was large enough so that all management operations could be completed using standard farm equipment.

Table 1 – Summary of soils information from the Lucas and Wayne County soil surveys

Series	Area (ha)[a]		Taxonomic classification[b]	Drainage class[c]
	Lucas	Wayne		
Arispe	0.6		Fine, smectitic, mesic Aquertic Argiudoll	SWPD
Clarinda	0.6	0.6	Fine, smectitic, mesic Vertic Argiaquoll	PD
Grundy	1.0		Fine, smectitic, mesic Aquertic Argiudoll	SWPD
Haig	0.5		Fine, smectitic, mesic Vertic Argiaquoll	PD
Seymour		0.4	Fine, smectitic, mesic Aquertic Argiudoll	SWPD
Shelby		0.1	Fine-loamy, mixed, superactive, mesic Typic Argiudoll	
Total	2.7	1.1		

[a] Data from Lockridge [7] and Boeckman [8].
[b] Classification from Soil Survey Staff, 2004 [9].
[c] SWPD and PD refer to somewhat poorly and poorly drained, respectively.

2.2. *Field data collection*

Biomass samples were collected for each nitrogen treatment at each landscape position in August 1998 and 1999. At each sampling period, a 1-m^2 sample from a predetermined position at each landscape position within each plot was clipped by hand at ground level. Plots were also sampled at the time of the entire plot harvest in all years except 2002. Samples were oven dried at 60 °C for 72 h to the determine dry matter yield. After drying, plant tissue was sequentially ground through a Wiley Mill (Thomas Manufacturing, Philadelphia, PA) to pass a 8 mm screen and a Cyclone Mill (UDY Manufacturing, Fort Collins, CO) to pass a 1 mm screen. Samples of homogenized tissue were stored in plastic bottles until quality analysis was performed.

Switchgrass plots were harvested for total seasonal yield after the first killing frost caused above-ground growth to cease. Harvest dates were 27 November 1998, 27 September 1999, 17 October 2000, 20 November 2001, and 20 November 2002. Switchgrass was cut to ground level using a conventional mower conditioner and allowed to field dry for at least 5 days. The plots were baled into small square bales (1998 and 1999) or large round bales (2000–2002), which were individually weighed. Sub-samples at each landscape position were collected, weighed, dried at 60 °C for 72 h, and re-weighed for dry matter determinations. The average dry matter across landscape positions was used to adjust the whole plot yield. Fertilizer N use efficiency (FUE) was calculated according to Anderson et al. [10]:

$$\mathrm{FUE} = \frac{\text{N treatment yield} - \text{no N treatment yield}}{\text{N applied}} \times 100$$

In 1998 and 1999, canopy height was measured at harvest for each landscape position using a modified rising plate meter [11]. The rising plate meter consisted of a 0.929 m^2 plexi-glass plate with a 1.3 cm hole in its center, through which a 1.3 cm electric aluminum tube marked at 1 cm intervals was inserted. The plate was dropped from a uniform distance of 10 cm above canopy and the height was measured at the point on the pole where the plate came to rest. Two measurements at each landscape position, taken at random positions, were averaged for statistical analysis. Lodging was estimated in November 1998 and in August 1999 as the percentage of plants within the whole plot that were lodged more than 35° from the vertical.

2.3. *Biomass quality analysis*

Concentrations of the cell wall constituents, neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL), ash and N were based on near-infra-red spectroscopy calibrated with wet chemistry. Samples were scanned using a scanning monochromator to collect reflectance measurements (log 1/*R*) between 1100 and 2500 nm, recorded at 4-nm intervals (Model 6500, NIRS Systems, Silver Springs, MD 20910). Scanning and calibration were performed independently for the 1998 and 1999 samples and the 2000 and 2001 samples. No analysis of 2002 samples was conducted. A subset of scanned samples (approximately 10%) was identified for wet chemistry analyses based on spectral properties [12]. Calibration equations were calculated using modified partial least squares regression [13]. For the 1998 and 1999 samples, coefficients of determination (R^2) and standard errors of the calibration and cross validation were 0.97, 1.33, and 1.59 for NDF; 0.97, 1.07, and 1.23 for ADF; 0.95, 0.44, and 0.61 for ADL; 0.77, 0.70, and 0.76 for ash; and 0.99, 0.03, and 0.05 for N. For 2000 and 2001 samples, coefficients of determination (R^2) and standard errors of the calibration and cross validation were 0.99, 0.21, and 0.86 for NDF; 0.97, 0.44, and 0.89 for ADF; 0.91, 0.24, and 0.39 for ADL; 0.97, 0.16, and 0.35 for ash; and 0.99, 0.01, and 0.03 for N.

Calibration data were determined using an ANKOM 200 Fiber Analyzer (ANKOM Technology Corp., Fairport, NY 14450), as described previously [14]. Hemicellulose was calculated as NDF–ADF and cellulose as ADF–ADL. Nitrogen was determined using the micro-Kjeldahl procedure [15], and ash content (g kg^{-1}) was determined by combustion of 1 g of plant tissue in a muffle furnace at 550 °C for 4 h.

2.4. Ultimate, proximate, and elemental analyses

Samples collected in 1999 and 2000 from three replications at each location and not including the $56\,kg\,ha^{-1}$ nitrogen treatment were used for ultimate, proximate, and elemental analyses. Ultimate and proximate analyses were performed by Hazen Research, Inc. (Golden, CO) using ASTM D3176 for the ultimate analysis and evaluating O by difference, and ASTM D3172 for the proximate analysis, determining fixed C by difference. In both cases, ashing was done at 600 °C instead of 800 °C. Energy density (higher heating value or gross calorific value) was determined using ASTM D3286. Analysis of elements and major oxides was performed by Activation Labs Ltd. (Ancaster, Ontario, Canada). Ash, produced by combustion at 475 °C, was mixed with a flux of lithium metaborate and lithium tetraborate, fused at 1050 °C in an induction furnace, poured into a 5% nitric acid solution, mixed for 30 min to dissolve, and analyzed on a Thermo Jarell–Ash ENVIRO II inductively coupled plasma emission spectroscope. Elements including Cl were determined on ash prepared at 475 °C using instrumental neutron activation analysis.

2.5. Data analysis

Nitrogen level and years were considered to be fixed effects; locations and reps within locations were considered random. The experiment was analyzed as a split-plot in time, with years treated as a repeated measurement [16]. Locations were tested for significance using the replication within location mean square as the error term. Nitrogen level and the location by N level interaction were tested using the replication by N level within location mean square as the error term. Landscape positions were analyzed as subplots of nitrogen level. Single degree of freedom contrasts were used to test linear and quadratic effects of nitrogen levels and years. Data were analyzed using the GLM procedure of the SAS statistical software program [17]. Unless otherwise indicated, differences were considered to be significant at the 5% probability level.

3. Results and discussion

3.1. Biomass yield

Biomass yield increased from 1998 to 2002, indicating a positive cumulative effect of N fertilization over time (Table 2; Fig. 1). Location by nitrogen and location by year interactions were present, but no nitrogen by year or three-way interaction was evident. The mean yield in 2002, $6.5\,mg\,ha^{-1}$ averaged across locations and nitrogen levels, is $3.6\,mg\,ha^{-1}$ greater than that seen in 1998 from these same fields, which improves the feasibility of economically producing biomass in southern Iowa. The results from 2001 were aberrant, probably due to the delay in applying nitrogen until July and then in applying only one-third as much N as planned due to an error by the commercial applicator. Undoubtedly, this kept yields below their potential in 2001 and possibly had a carryover effect on 2002.

The response to nitrogen varied between locations; at the higher nitrogen levels and in later years, the Lucas site produced higher yields than the Wayne site (Fig. 1). The maximum yield attained to date was at Lucas in 2002, with plots receiving $112\,kg\,N\,ha^{-1}$ yielding $8.5\,mg\,ha^{-1}$ (Fig. 1). At Lucas, the application of $224\,kg\,N\,ha^{-1}$ boosted average yield across the 5 years by nearly $2\,mg\,ha^{-1}$ vs. the zero N treatment ($4.2–6.1\,mg\,ha^{-1}$), but the response at Wayne was half that ($4.2–5.1\,mg\,ha^{-1}$).

The yield response to N fertilizer was non-linear, with diminishing yields occurring at higher N levels (Fig. 2). From a fertilizer use efficiency standpoint, $56\,kg\,ha^{-1}$ is most efficient ($FUE = 2$); $FUE = 1.5$ for $112\,kg\,ha^{-1}$ and 0.85 for $224\,kg\,ha^{-1}$. However, the recommended fertilization rate for switchgrass biomass production in this region of southern Iowa would depend on the value of biomass relative to the cost of additional fertilizer.

These fields were previously enrolled in the CRP, receiving very limited management, and the yield improvement by simply applying standard agronomic management practices of nitrogen fertilization, weed control, and a single harvest per year was striking, especially after several years (Fig. 1). Simple management alone, without addition of any nitrogen, increased yields in the 0 N plots from 2.3 to $5.1\,mg\,ha^{-1}$ from 1998 to 2000, but no further increases in yield were observed (yields were 4.9 and $5.1\,mg\,ha^{-1}$ in 2001 and 2002, respectively). On average across the 5 years, adding $56\,kg\,N\,ha^{-1}$ improved yield by 20% over unfertilized controls; $112\,kg\,N\,ha^{-1}$ boosted yields by 32% and $224\,kg\,N\,ha^{-1}$ by 37%. However, the nitrogen effect is increasing over time. For example, in 2002, $112\,kg\,N\,ha^{-1}$ increased yield by 41% over unfertilized control plots (data not shown). Thus, while management operations other than fertilization can make certain improvements initially, the beneficial effects of nitrogen are continuing and increasing. The potential for continued increases in yields appears favorable.

Despite a combination of variable weather, site limitations (e.g., the fields consist of soils with high-clay argillic horizon limitations), and fertility and/or stand deficiencies (e.g., some areas in the plots have observably thin stands), we have produced biomass yields as high as $8.5\,mg\,ha^{-1}$. In addition to continued gains simply from using best management practices, further yield gains could come from changing cultivars. We showed that Cave-In-Rock, the currently recommended variety for southern Iowa, yielded substantially less than lowland cultivars including 'Alamo' or 'Kanlow' [18]. We are encouraged that our yield at Lucas in 2002 ($8.5\,mg\,ha^{-1}$) is very close to the average yield of Cave-In-Rock ($9.3\,mg\,ha^{-1}$) we obtained in small plot trials several miles from the farm used in this experiment. Thus, the yield advantage of the lowland cultivars (about $3.5\,mg\,ha^{-1}$) may translate directly into improvements in commercial fields.

Landscape effects were measured for biomass yield and canopy height in August 1998 and 1999. Average biomass yield was significantly influenced by landscape position in August but not in July (data not shown). In August, averaged over both years, summits yielded more ($576\,g\,m^{-2}$) than either footslopes ($512\,g\,m^{-2}$) or backslopes ($502\,g\,m^{-2}$), which were similar. Although landscape position had a significant effect on yield across years, the difference was due to a large effect

Table 2 – Switchgrass yield, fiber content, nitrogen, and ash in two southern Iowa locations and at four nitrogen fertilization rates from 1998 to 2002 and interactions among locations, nitrogen levels, and years

	Yield $(\mathrm{mg\,ha^{-1}})$	Hemicell[a] $(\mathrm{g\,kg^{-1}})$	Cellulose $(\mathrm{g\,kg^{-1}})$	Lignin $(\mathrm{g\,kg^{-1}})$	N $(\mathrm{g\,kg^{-1}})$	Ash $(\mathrm{g\,kg^{-1}})$
Grand mean	5.0	316.7	387.7	69.1	4.7	48.3
By nitrogen rate						
0	3.9	322.5	380.6	66.0	4.8	51.2
50	4.5	318.4	389.6	68.7	4.5	47.8
100	4.9	318.0	384.5	68.8	4.6	48.1
200	5.2	307.7	396.1	72.9	5.1	46.0
Linear	****	**	**	***	*	**
Quadratic	**	ns	ns	ns	*	ns
By location						
Lucas	4.9	316.9	381.8	66.2	4.4	50.3
Wayne	4.3	316.4	393.6	72.0	5.1	46.3
Contrast	ns	**	ns	*	*	ns
By year						
1998	2.9	321.1	379.0	75.9	3.5	43.4
1999	3.9	296.6	343.4	70.7	5.5	56.1
2000	6.0	319.6	395.5	63.0	5.9	49.8
2001	5.6	329.2	433.0	66.7	4.2	43.9
2002	6.5	–	–	–	–	–
Linear	****	****	***	****	***	ns
Quadratic	**	****	****	***	****	****
Interactions						
Loc × N	*	ns	ns	ns	ns	ns
Loc × year	***	*	ns	ns	*	*
N × year	ns	ns	*	ns	ns	ns
Loc × N × year	ns	ns	ns	ns	ns	ns

[a] Hemicellulose calculated as NDF–ADF; cellulose as ADF–ADL; lignin = ADL.

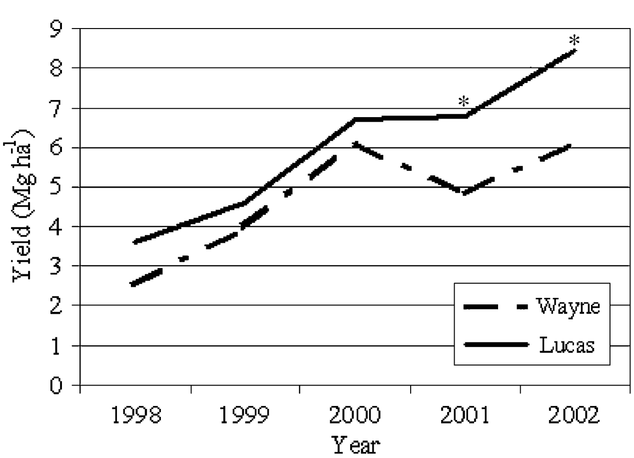

Fig. 1 – Switchgrass biomass yield at two Iowa locations fertilized annually with one application of nitrogen at 112 kg ha^{-1}. The asterisk (*) indicates the locations differed in the specified year ($p<0.05$).

in 1999, when the summits produced over 100 g m^{-2} more than the other two positions, a landscape effect that was not observed in 1998. These results were not surprising given the better soil depth and quality at this location. Because sediment deposition at the base of the slope increases nutrient availability and moisture content, we expected that the footslope would have produced a higher biomass yield than the backslope [19]. The end-of-year plot harvests were made across landscape positions and thus we do not have this information on specific landscape points. Plant height increased coincident with yield from 1998 to 1999 (118 vs 145 cm, respectively), but did not differ among the landscape positions, with the exception of July 1999, when switchgrass on the summits was taller (but only by 5 cm; $p<0.05$) than the others (data not shown).

3.2. *Cell wall components, nitrogen content, and ash*

As nitrogen fertilization rate increased, cellulose, lignin, and nitrogen increased, while hemicellulose and ash declined (Table 2). These changes are desirable, given the higher energy density in lignin and cellulose compared to hemicellulose and the potentially detrimental effects of ash to the power plant. Few differences were observed among landscape positions for biofuel quality traits of fiber, N, and ash concentration, and those that were statistically significant were not biologically relevant (data not shown). Of the two locations, Wayne had slightly higher levels of cellulose, lignin, and nitrogen (Table 2). Interestingly, Wayne had the lower yield, which casts the relationships among these traits in a different light than do the nitrogen level results above. No location by nitrogen treatment interactions was observed for any of these traits. A location by year interaction was noted for hemicellulose, N, and ash, and a nitrogen by year interaction for cellulose, but otherwise, no interactions were present (Table 2).

Cell wall constituents differed among years, with strong linear and quadratic responses noted for all traits except linear response for ash (Table 2). Because the sampling of biomass for analysis occurred at different dates each year (November 1998, September 1999, October 2000, and November 2001), differences cannot be attributed solely to year effects; the effect of year can be most directly compared between the 1998 and 2001 samplings, which occurred at nearly identical calendar dates. Significant quadratic contrasts suggest that earlier harvests result in biomass with

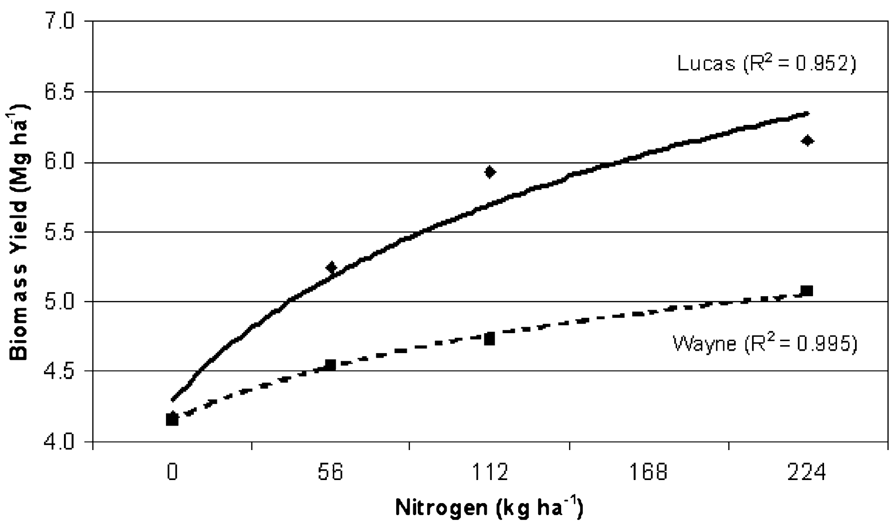

Fig. 2 – Switchgrass biomass yield at two Iowa locations fertilized with 0, 56, 112, or 224 kg N ha^{-1}.

Table 3 – Proximate and ultimate analyses of switchgrass biomass from 1998, 1999, and 2000 in two southern Iowa locations and at three nitrogen fertilization rates

	Caloric value[a] (MJ kg^{-1})	Ash (% Dry weight)	Volatile matter (% Dry weight)	Fixed carbon (% Dry weight)	C (% Dry weight)	H (% Dry weight)	N (% Dry weight)	O (% Dry weight)	S (% Dry weight)
Grand mean	18.22	4.36	79.21	16.43	47.58	5.45	0.40	42.17	0.063
By nitrogen rate									
0	18.18	4.74	78.96	16.31	47.37	5.48	0.38	42.00	0.071
100	18.22	4.41	79.29	16.30	47.52	5.44	0.39	42.19	0.062
200	18.25	3.93	79.39	16.68	47.86	5.42	0.41	42.32	0.055
Linear	ns	**	ns	*	**	ns	ns	*	**
Quadratic	ns	ns	ns	ns	ns	ns	ns	ns	ns
By location									
Lucas	18.17	4.64	78.87	16.49	47.45	5.44	0.38	42.03	0.060
Wayne	18.27	4.08	79.55	16.37	47.71	5.45	0.41	42.31	0.065
Contrast	ns	ns	*	ns	ns	ns	ns	ns	ns
By year									
1998	18.34	4.10	80.56	15.34	48.25	5.26	0.25	42.08	0.062
1999	18.33	4.86	78.35	16.79	46.94	5.52	0.25	42.40	0.063
2000	17.99	4.12	78.73	17.14	47.56	5.56	0.68	42.02	0.063
Linear	****	ns	***	****	**	***	****	ns	ns
Quadratic	**	**	***	***	***	ns	***	ns	ns

[a] Higher heating value (HHV) or gross calorific value (GCV).

lower fiber and higher ash and nitrogen, probably because soluble material had not been leached as severely as at later sampling dates. The linear trend is for hemicellulose, cellulose, and nitrogen to increase and ash and lignin to decrease across years, as yield increases were being made (Table 2).

The real significance of these results for biomass quality is unclear, but the main conclusion from these data seems to be that although the cell wall content of switchgrass biomass can vary due to year (or harvest date), location, or fertility effects, none of the differences was large enough to effect the overall biomass quality. Importantly, increases in yield do not appear to have any negative effects on cell wall constituents.

3.3. *Proximate, ultimate, and elemental analyses*

On average, the energy concentration in switchgrass biofuel was 18.22 MJ kg^{-1} (Table 3). Neither nitrogen rate nor location affected the energy concentration of the switchgrass biofuel, but biomass produced in 2000 had a lower value than from previous years. Minor changes were observed across nitrogen levels for concentrations of ash, which declined, and of fixed carbon, which increased. Volatile matter was unchanged. Across years, differences of less than 2% of dry mass were observed for both volatile matter and fixed carbon. For ultimate analyses, as nitrogen levels increased, ash and sulfur concentrations declined and carbon and oxygen levels increased. Differences in most variables were revealed among years, although interpretation of these differences is again complicated by different harvest dates. Location differences were almost completely absent. No two- or three-way interactions among location, nitrogen level, or year were present, except a location by nitrogen level interaction for N concentration ($p<0.05$, data not shown). Thus, the few differences we observed in this experiment for proximate and ultimate analyses were all relatively small, and probably would have little (if any) impact on using switchgrass as a biofuel.

For most elements and major oxides, little effect of nitrogen level, year, or location was present (Table 4) and the values were broadly congruent with those found previously for switchgrass [6,20]. The differences observed between years or locations, or across nitrogen levels for any of the elements are probably immaterial in terms of biofuel quality. Some differences of note included a 4% decline in SiO_2 across N levels, a doubling of P_2O_5 from Wayne to Lucas, and a nearly fivefold increase in Mo at Wayne compared to Lucas.

Table 4 – Concentrations of major oxides and elements in ash of switchgrass biomass and variation between two years, two locations, or across three nitrogen fertilization treatments

Elem	Unit	Mean	Std dev	Year	Loc	N linear
SiO_2	%	56.28	4.34	ns	*	(−)***
Al_2O_3	%	0.22	0.06	ns	ns	ns
Fe_2O_3	%	0.15	0.06	ns	ns	(+)**
MnO	%	0.23	0.08	ns	ns	ns
MgO	%	4.41	0.86	ns	*	ns
CaO	%	7.48	0.97	ns	*	(+)**
Na_2O	%	0.18	0.29	ns	ns	ns
K_2O	%	12.15	2.22	*	ns	ns
TiO_2	%	0.015	0.008	**	ns	ns
P_2O_5	%	3.39	1.26	ns	**	(−)***
LOI[a]	%	15.00	4.19	ns	*	(+)**
Ba	ppm	300	96	**	ns	(+) *
Br	ppm	149	69	ns	ns	ns
Ca	ppb	6.10	1.14	*	ns	ns
Cl	ppm	885	377	ns	ns	ns
Co	ppm	5.33	2.38	ns	*	ns
Cr	ppm	7.61	2.45	ns	ns	ns
Fe	%	0.10	0.03	*	ns	ns
K	%	13.77	3.05	**	ns	(+)**
Mo	ppm	9.39	8.05	ns	***	ns
Na	ppm	288	60	ns	ns	ns
Rb	ppm	53	21	ns	ns	ns
Zn	ppm	402	112	**	ns	ns

[a] LOI = lost on ignition.

3.4. *Prospects for biomass production in Southern Iowa*

The results of this experiment suggest that combining high biomass yields with acceptable biofuel quality can be achieved, and that some management practices can actually meet both goals simultaneously. Increasing biomass yields did not have detrimental effects on biofuel quality. The negative effect of added N is that it could accelerate lodging of biomass harvested at the end of the growing season. Although lodging was not a major problem in this experiment, it increased at higher nitrogen rates in both years in which it was measured (to a maximum of about 20%, data not shown), and should be considered when making management decisions.

Delaying harvest in the fall could increase lignocellulose components, while decreasing total N and ash. How long harvest can be delayed depends on the potential for yield loss, or worse, bad weather precluding harvest altogether. Biomass quality components differed more among years than among N treatments, indicating that environmental variables—harvest date probably being the most important—play a larger role than N rates in influencing biomass quality. High ash and mineral concentrations such as Cl and S could cause problems in combustion systems [20], but we saw little variation for most elements, either among years, locations, or N levels.

Management of switchgrass for both forage and biofuel production would improve the cropping options available to farmers in the Chariton Valley. This experiment has shown on large, commercial-scale plots that switchgrass yields can be improved through appropriate management practices by as much as 5.0 kg ha^{-1} over a 5-year period. Continued nitrogen fertilization should further improve the yields, at least at the Lucas location, since no plateau effect has yet occurred. At the Wayne location, yield may have plateaued, although the effect of the misapplication of N in 2001 may have caused that effect.

We conclude from this experiment that a single switchgrass harvest in the fall, between September and November, produces a high-quality biofuel. Nitrogen fertilization had minimal impacts on traits other than yield and was used most efficiently by the switchgrass plant at levels between 56 and 112 $kg\,N\,ha^{-1}$.

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