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Sweet Sorghum [*Sorghum bicolor* (L.) Moench] Biomass Production for Biofuel and the Effects of Soil Types and Nitrogen Fertilization

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This research aimed to determine the optimum nitrogen fertilization rate on three soils for producing biomass sweet sorghum (Sorghum bicolor cultivar M81E) and corn (Zea mays cultivar P33N58) grain yield and to compare their responses. The research was conducted in Missouri in rotations with soybean, cotton, and corn. Seven rates of nitrogen (N) were applied. Sweet sorghum dry biomass varied between 11 and 27.5 Mg ha⁻¹ depending on year, soil type, and N rate. Nitrogen fertilization on the silt and sandy loam soils had no effect ($P > 0.05$) on sweet sorghum yield grown after cotton and soybean. However, yield increased in the clay soil. Corn grain yielded from 1.3 to 12.9 Mg ha⁻¹, and 179 to 224 kg N ha⁻¹ was required for maximum yield. Increasing biomass yield required N application on clay but not on silt loam and sandy loam in rotations with soybean or cotton.

Keywords Biofuel, biomass, corn, nitrogen, sweet sorghum

Introduction

BP Global (2006b) and the Energy Information Administration (Energy 2007a) estimate that the world's oil reserves will be depleted within the next 40 years. Production of fuels from biomass can make a significant contribution to solve the energy crisis (Berndes, Hoogwijk, and Van Den Broek 2003; Spiertz and Ewert 2009). For instance, by 2030, the United States is planning to replace 20% of the fuel used in transportation with energy produced from biomass (English and Ewing 2002). Therefore, understanding the parameters that affect biomass yield is critical to advance specific crops for use in biofuel (Wullschleger et al. 2010). Corn and sweet sorghum are among the plants that hold promise for biofuel production (Balat 2007; Patzek 2006; Zuurbier and van de Vooren 2008). Sweet sorghum tolerates drought better than corn (Tesso, Claflin, and Tuinstra 2005; Tsuchihashi and Goto 2004). It also tolerates salinity and flooding (Almodares, Hadi, and Ahmadpour

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2008; Netondo, Onyango, and Beck 2004). Its short growing cycle leads to the possibility of having more than one crop per year. The juice in sweet sorghum stalks can be fermented into ethanol. The bagasse obtained after removing the juice from stalks could also be processed into gas or ethanol (Gnansounou, Dauriat, and Wyman 2005; Monti and Venturi 2003; Sipos et al. 2009). Corn grain is rich in starch that can be converted into ethanol. Currently, the amount of biofuel produced from corn surpasses that produced from sugarcane in Brazil (Karp and Shield 2008).

Nitrogen (N) is the most frequently applied fertilizer to increase crop yield. However, if used in excess, N is detrimental to the environment and the extra costs reduces farmers' income (Rashid and Voroney 2005). When nitrogen is applied to crops, a significant proportion can be lost in the atmosphere in a form of nitrous oxides (Crutzen et al. 2007; Ruser et al. 1998). Unfortunately, nitrous oxide is 300 times worse than carbon dioxide in damaging the ozone layer, which leads to global warming (Crutzen and Ehhalt 1977). The amount of N used as a fertilizer in agriculture is predicted to triple by 2050 (Subbarao et al. 2009), suggesting that its negative impact on the environment will also increase. Therefore, the high cost of N to attain maximum yields (Bolck 1984), its negative environmental impact (Schepers et al. 1991; Vitousek et al. 1997), and the amount of biofuel needed to meet future energy demands make it very important to study ways to properly manage N fertilization. Efficient and optimum use of N is a key to properly managing crops for biomass production to produce biofuel. Very little research is available on how N affects bioethanol production in sweet sorghum in the United States. In the few studies conducted to date on the impact of N fertilization on the biomass production of sweet sorghum, results were inconsistent. A recent study of the impact of urea on the biomass production of sweet sorghum showed that the biomass yield depended on the year but not always on the N rate (Tamang 2010). In contrast to sweet sorghum, extensive work has been done on the impact of N on corn grain yield (Amanullah 2010; Binder, Sander, and Walters 2000; Hawkins et al. 2007; Kahabka et al. 2004; Ruiz Diaz et al. 2008; Scharf, Wiebold, and Lory 2002). In general, with few exceptions (Halvorson et al. 2005), N application always improved corn grain yield. Generally, most of the studies of corn grain for biofuel production reported an optimum N fertilization rate ranging from 138 to 152 kilograms of N per hectare (kg N ha^{-1}) (Keeney and Deluca 1992; Lorenz and Morris 1995; Pimentel 1991, 2001; Shapouri, Duffield, and Graboski 1995; Shapouri, Duffield, and Wang 2002). No one has done side-by-side comparisons of N response in sweet sorghum biomass to corn grain production on a range of soil textures to produce biofuel feedstock. Missouri is one of the states whose ecology is well suited for bioethanol feedstock production. No research has been published on how some Missouri soils respond to N fertilization on biomass production for conversion into ethanol. The present hypothesis is that (1) N fertilization responses of sweet sorghum biomass and corn grain are different and (2) the optimum N fertilization rate needed for maximum sweet sorghum biomass production may vary by soil type. The objective of this research was to determine the optimum N fertilizer rate on three soils for producing sweet sorghum biomass. In this paper, because of the extensive research already conducted on the impact of N on corn yield, the emphasis will be placed on response of sweet sorghum with data for corn used for comparative purposes.

Materials and Methods

Initial Soil Analysis

The research was conducted in Missouri over a 3-year period (2007–2009) on alluvial soils laid down by the Mississippi River. Test sites were selected with a range of soil textures.

The experiment was done on a Tiptonville silt loam (fine-silty, mixed, superactive, thermic Oxyaquic Argiudolls), a Sharkey clay (Vertisol, aquerts, epiaquerts, chromic, very fine, smectitic, thermic), and a Malden sandy loam (entisols, psamment, udipsamments, typic, mixed, thermic). The silt loam and the clay soils was located at the University of Missouri–Lee Farm near Portageville (36° 25' N, 89° 41' W), whereas the sandy loam was at Clarkton (36° 27' N, 89° 58' W) at the University of Missouri–Rhodes Farm. The Clarkton and Portageville sites are 28 km apart. Only the loam soil type was studied during the first year of the experiment. In the following 2 years, the research was extended to all three soil types. The fields used in 2007 had been previously planted in cotton and in 2008 in soybean. In 2009, the sorghum planted on the clay soil followed soybean, the sorghum planted on the loam followed corn, and the sorghum planted on the sand was after cotton. Seven to 10 days after the seeds were planted, soil samples were randomly taken in each field at 0–15 cm deep. These soil samples were dried in an oven and analyzed for their nutrient content. Soil organic-matter content was measured by the loss on ignition method (Storer 1984). Soil pH_{salt} was measured with a glass electrode in 0.01 mol of calcium chloride (M CaCl₂) salt solution and neutralizable acidity (NA) was measured in Woodruff buffer solution (Brown and Rodriguez 1983; Woodruff 1967). Potassium (K), calcium (Ca), and magnesium (Mg) were extracted in 1 N ammonium acetate and measured on an atomic absorption spectrophotometer (Thomas 1982). Phosphorus was measured colorimetrically using Bray 1 extraction solution (Bray and Kurtz 1945). Cationic exchange capacity (CEC) was calculated by summing the neutralizable acidity with the K, Mg, and Ca concentrations in meq 100 g⁻¹ soil (Brown and Rodriguez 1983).

Experimental Design

The sweet sorghum cultivar planted was M81E, whereas the corn cultivar was P33N58. Corn was grown as a check for the sweet sorghum response to N for comparative purposes. The experimental design was a four-replicate, randomized complete block. For sweet sorghum, each block consisted of seven N treatments: 0, 22, 45, 67, 90, 112, and 135 kg N ha⁻¹; whereas for corn, the N rates applied were 0, 45, 90, 134, 179, 224, and 269 kg N ha⁻¹. Each N treatment corresponded to a plot. Each plot consisted of 4 rows spaced 76.2 cm apart. Sweet sorghum seeds were planted (Table 1) in early May at a density of 296,516 seeds ha⁻¹ compared to 79,071 seeds ha⁻¹ for corn. In contrast, corn was planted mid- to late April (Table 1). Less than 2 weeks after planting, both crops received two applications of atrazine (2-chloro-4-ethylamine-6-isopropyl amino-S-triazine) at 1.1 kg ha⁻¹ active ingredient to control weeds. The applications were 2 weeks apart. Additionally, the field was regularly hoed as needed to reduce weeds not controlled by the herbicides. Three weeks after planting, the appropriate N rate was broadcast by hand on each plot using ammonium nitrate. Ammonium nitrate (17% nitrate N, 17% ammonium N) was chosen because it does not have the potential for ammonia volatilization like urea, simplifying the test by minimizing and removing the uncertainty of ammonia losses. The field was irrigated as needed to optimize production. The sandy soil was irrigated with linear move sprinkler irrigation, whereas the loam and the clay soil were furrow irrigated. Five furrow irrigations (76-mm water applications) per year were made on the loam and clay compared to six to eight sprinklers (25-mm applications) per year on the sand.

Biomass Harvest

The sweet sorghum heads were removed by hand in the early dough stage, which is about a month before the harvest of the biomass. Researchers were interested in maximizing sugar

Table 1
Planting date of corn and sweet sorghum at Portageville and Clarkton, Missouri,
2007–2009

Crop	2007	2008			2009		
	Loam	Loam	Clay	Sand	Loam	Clay	Sand
Corn	27 March 2007	16 April 2008	17 April 2008	23 April 2008	27 April 2009	27 April 2009	17 April 2009
Sweet sorghum	8 May 2007	19 May 2008	21 May 2008	21 May 2008	20 May 2009	19 May 2009	15 May 2009

content in the juice from stalks; therefore, no seeds were harvested at the end of the season. Four and a half months after germination, sweet sorghum was harvested using a hay sickle mower. In each plot, 1.8 m of the two center rows was used for data collection in which the whole biomass was harvested. The fresh weight was taken in the field immediately after harvest. One representative plant per plot was cut and separated into leaves and stalk. The fresh weight of the corresponding leaves and stalk were recorded. These samples from each plot were later dried in an oven and weighed periodically until the weights ceased changing. At that time, the biomass was considered completely dry. From the dried samples, the water content of the biomass was calculated. Then, using the weight of the biomass harvested within the 1.83 m previously measured, the biomass yield per hectare was determined. In the case of corn, the two middle rows in each plot were harvested at maturity using a plot combine. Corn grain yield was calculated per plot based on 15% moisture content. The stover yield was not collected because to date it has not been a major target for biofuel production.

Calculations of Sweet Sorghum Biomass Production

The fresh stalk expression (stalk to whole biomass ratio) was calculated by dividing the weight of the fresh stalk by that of the fresh biomass (stalk + leaves) derived from sampled plants. The stalk yield was calculated by multiplying the biomass yield by the stalk expression. The yield of the leaves was obtained by subtracting the stalk yield from the total biomass yield. The water content (fresh-weight basis) was calculated by subtracting the dry weight from the fresh weight and then dividing the difference by the fresh weight. The water accumulation (or water uptake) in the biomass is the amount of water sequestered in the biomass. In the case of the stalk, the water accumulation was calculated by multiplying the water content of the stalk by the fresh stalk yield. The water accumulation of the leaves was calculated by multiplying the water content of the leaves by the fresh leaves yield. Then, the water accumulation of the stalk and the leaves were added to yield the water accumulation in the whole aboveground biomass. The dry yield of the stalk and that of the leaves were calculated by subtracting the water accumulation in the stalk and that in the leaves from the fresh stalk yield and the fresh leaves yield respectively. The total dry biomass yield was calculated by adding the dry yield of the stalk and that of the leaves. More details about the methodology can be found in the previous articles related to this publication (Holou and Kindomihou 2011; Holou and Stevens 2012; Holou, Stevens, and Kindomihou 2011).

Statistical Analysis

The data were analyzed using the linear mixed model in SAS 9.2 (SAS Institute Inc., Cary, N.C.). Significant differences were assumed for $P \leq 0.05$. The year, the soil type, and the N rate were considered the main fixed factors, whereas the blocks (replicates) were classified as a random variable. For the linear mixed model, the estimation method was the restricted maximum likelihood (REML). When a significant difference was found based on the year or the soil type, the test was repeated for each year and each soil type separately. Means were separated and grouped by letter by using the macro developed by Saxton (1998). Significant differences were assumed for $P \leq 0.05$.

Results

Initial Soil Fertility Summary

The initial soil fertility in the silt loam and the sandy loam soils were more similar, whereas the clay constituted a separate situation. In general, the average organic-matter content of the clay soil (3.7%) was four to six times greater than that in the loam and the sand, respectively. Phosphorus was the main nutrient that was lacking in the clay soil. The nutrient content in the soil varied among years (Table 2).

Weather Summary

The daily precipitation did not depend on the year (probability of significance $P = 0.095$) nor on the soil type ($P = 0.86$). However, the temperature, vapor pressure, maximum wind speed, and total solar radiation significantly varied along the years (Table 3). The minimum, maximum, and average temperatures did not significantly vary across each location. However, the maximum wind was the only variable that differed across the soil type. In general, the speed on the wind was greater at Clarkton, Missouri, on the sandy loam soil than at Portageville for the other soils.

Corn Grain Yield

The grain is currently the feedstock primarily used for the production of biofuel from corn. Therefore, the grain yield was the focus of this experiment. The grain yield of corn significantly depended on the year ($P < .0001$), the N rate ($P < .0001$), and the soil type ($P < .0001$) (Tables 4 and 5). In general, the grain yield ranged from 1.29 to 12.88 Mg ha⁻¹ (Table 6), with the lowest and the greatest yields obtained with 0 and 179 kg N ha⁻¹ respectively. In 2009, about 1 week after emergence, the clay soil type was flooded by rain and stands of the corn seedlings were reduced. By the time the field dried out, it was too late to replant the plots on the clay to achieve satisfactory yields. The poor stands resulted in erratic plot yields because many plants died from the excessive water. Therefore, the 2009 corn yield data on clay soil was unreliable and omitted from the statistical analysis.

Sweet Sorghum Fresh Biomass

The year, soil, and N rate had significant effects on the total fresh biomass yield of sweet sorghum ($P < .0001$) (Tables 4 and 5). There was a significant interaction between the soil

Table 2
Soil-test values for several soil characteristics at Portageville and Clarkton, Missouri, in 2008 and 2009

Variable	2008			2009			Average		
	Clay ^a	Loam	Sand	Clay	Loam	Sand	Clay	Loam	Sand
pH	6.0	6.1	5.1	6.1	5.5	6.0	6.0	5.8	5.6
NA (meq/100 g)	2.6	1.2	1.6	1.9	2.3	1.7	2.3	1.8	1.7
OM (%)	4.1	1.4	0.6	3.2	0.9	0.6	3.7	1.1	0.6
CEC (meq/100 g)	40.6	8.9	4.8	34.3	10.3	6.2	37.7	9.6	5.7
P Bray I (mg kg ⁻¹)	24.1	37.6	29.1	28.4	48.6	35.1	26.1	43.1	32.7
Ca (mg kg ⁻¹)	5183.9	1322.3	408.7	4473.1	1180.9	648.0	4852.2	1251.6	552.3
Mg (mg kg ⁻¹)	1339.3	90.5	108.3	1132.5	226.8	120.6	1242.8	158.6	115.7
K (mg kg ⁻¹)	340.1	137.8	85.8	231.5	78.7	120.6	289.4	108.3	106.7

^aThe soil was analyzed at the beginning of the growing season. The P content of the clay is lower than that of the other soils.

Notes. OM, organic matter; NA, neutralizable acidity; pH, potential hydrogen.

Table 3
Weather summary from growing seasons at Portageville and Clarkton, Missouri,
2007–2009

Weather	Year	April	May	June	July	August	September
Total monthly precipitation (mm)	2007	70.9	66.3	44.6	72.8	20.9	124.1
	2008	143.8	93.1	35.2	67.1	45	74.1
	2009	139.9	171.2	69.9	106.6	54.9	119.5
Maximum air temperature (°C)	2007	19.9	28.8	32.1	31.3	35.9	30
	2008	19.1	25.6	32	32.9	30.8	28.2
	2009	20.7	24.8	32.5	30	30	27.6
Minimum air temperature (°C)	2007	8	16.8	19.7	20	22.5	17.8
	2008	8.3	14.1	20.5	21.6	19.8	16.2
	2009	9.3	15.4	20.8	20.1	18.7	17.2
Average air temperature (°C)	2007	14	22.6	25.8	25.6	28.8	23.5
	2008	13.8	20	26.2	26.9	24.9	21.8
	2009	14.8	20.1	26.5	24.8	24	21.8
Total solar radiation (MJ/M ²)	2007	20	20.9	21.8	23.6	22.2	16.2
	2008	16.5	17.8	21	20.8	18.9	15.1
	2009	16	16.5	21.1	18.8	20.3	13.8
Vapor pressure (KPA)	2007	0.7	1.1	2.1	2.3	2.4	2
	2008	1.2	1.6	2.1	2.5	2.3	1.9
	2009	1.2	1.8	2.3	2.2	2.3	2.1
Vapor pressure deficit (KPA)	2007	1.1	1.7	1.3	1.1	1.7	1
	2008	0.5	0.8	1.4	1.2	0.9	0.8
	2009	0.6	0.7	1.3	1	0.8	0.6

type and the year. In general, the loam and the sand did not show a significant biomass yield response to N fertilization ($P > 0.05$). In contrast, the impact of N was significant in 2009 on the clay ($P = 0.002$). During the separate years of the study, the average total fresh biomass varied between and 91.6 Mg ha⁻¹. Nitrogen fertilization did not affect the stalk yield in either 2007 or 2008, but stalk yield was significantly increased from N fertilization in 2009 on all soil types. In 2009, the maximum stalk yield in the clay (54.9 Mg ha⁻¹) and the loam (45.7 Mg ha⁻¹) was obtained with the application of 134 kg N ha⁻¹. Particularly, the stalk yield was significantly associated with the N rate on the loam and the sand in 2009. That year, the yield on the clay was greater than that of the loam. Nitrogen fertilization did not affect the fresh leaf yield on any soil type. The partitioning of the total biomass between the leaves and the stalk was dependent on the year or the N rate, but not on the soil type. In the sand, sweet sorghum produced 93% of its biomass in the stalk, whereas in the clay, that ratio was 87%.

Water Content in Sweet Sorghum Biomass

In contrast to corn grain, sweet sorghum biomass at harvest contained a large amount of water at harvest. Water in the biomass impacts transportation costs as well as the storage. Overall, more than 90% of the total water in the biomass was in the stalk. Each year, the sorghum grown in the sandy loam had more water in the stalk than plants from the loam

Table 4

Impact of the year, soil type, and the N rate on the response of the biomass variables in Portageville and Clarkton, 2007–2009

Crop	Variable	Year (Y)	Soil Type (S)	N rate (N)	Y × S	N × Y	S × N	S × N × Y
Corn	Corn grain	****	****	****	****	*	ns	ns
	Sorghum fresh total biomass	****	****	****	****	ns	ns	ns
	Fresh stalk yield	****	****	****	****	ns	ns	ns
	Fresh leaf yield	****	****	ns	****	ns	ns	ns
	Stalk yield: (stalk + leaf yield)	ns	****	ns	ns	ns	ns	ns
Sweet sorghum	Water content stalk	****	****	ns	***	ns	ns	ns
	Water uptake stalk	****	****	****	****	ns	ns	ns
	Water uptake leaf	**	****	ns	*	ns	ns	ns
	Water uptake whole biomass	****	****	****	****	ns	ns	ns
	Dry leaf yield	****	****	ns	****	ns	ns	ns
	Dry stalk yield	****	****	****	****	ns	ns	ns
	Total dry biomass yield	****	****	****	****	ns	ns	ns

Notes. $P < 0.0001$, ****; $P < 0.001$, ***; $P < 0.01$, **; $P < 0.05$, *; $P < 0.05$, ns (nonsignificant). P , probability of significance.

and clay. The stalk water content ranged from 67% to 78%. The water amount in the stalk ranged from 15.6 to 69.54 Mg ha⁻¹, and it was not significantly affected by N fertilization in 2 of the 3 years. In 2009, the application of N increased the amount of water accumulated in stalk. The water uptake on the loam and on the clay in 2009 linearly increased as the N rate also increased. A lot of the differences in tissue moisture at harvest may be due to range in planting dates, rainfall, and irrigation amounts.

Sweet Sorghum Dry Biomass

Sweet sorghum dry biomass yield was significantly affected by year and soil type (Tables 4 and 5). The impact of N on the dry yield is generally more pronounced in the stalk ($P < .0001$) than in the leaves ($P = 0.46$). The impact of N on the dry stalk yield from the clay was always statistically significant during the course of this study. In 2009, the stalk dry yields improved with the increased application of N on all soil types (Tables 5–10). The dry stalk yield averaged between 3 and 6 times more than that of the leaves. Unlike results on the clay, variability between the years was not significant on loam and sand. Each year, the stalk accounted for about 82% of the total dry biomass on the loam compared to 85% on the sand. The average dry biomass yield ranged from 11 to 27 Mg ha⁻¹. The dry stalk yield varied between 9.44 and 22.53 Mg ha⁻¹, whereas that of the leaves ranged from 1.6 to 4.93 Mg ha⁻¹. The greatest dry stalk yield was recorded on the loam and on the sand in 2008. In general, the dry stalk yield on the clay was positively correlated with N, whereas this relationship was observed only in 2009 on the loam.

Table 5
Impact of the N rate on the response of different corn and sweet sorghum biomass variables at Portageville, and Clarkton, 2007–2009

Crop	Variable	2007	2008			2009		
		Loam	Loam	Sand	Clay	Loam	Sand	Clay
Corn	Corn grain	****†	*	****	****	****	****	
	Sorghum total fresh biomass	ns	ns	ns	ns	ns	ns	**
	Fresh stalk yield	ns	ns	ns	ns	*	**	**
	Fresh leaf yield	ns	ns	ns	ns	ns	ns	ns
	Stalk: (stalk + leaf yield)	ns	ns	ns	ns	ns	ns	*
	Water content stalk	ns	ns	ns	ns	ns	ns	*
Sweet sorghum	Water uptake stalk	ns	ns	ns	ns	*	*	**
	Water uptake leaf	ns	ns	ns	ns	ns	ns	ns
	Water uptake whole biomass	ns	ns	ns	ns	*	*	**
	Dry leaf yield	ns	ns	ns	ns	ns	*	ns
	Dry stalk yield	ns	ns	ns	*	*	**	**
	Total dry biomass yield	ns	ns	ns	*	*	*	**

Notes. $P < 0.0001$, ****; $P < 0.01$: **, $P < 0.05$, *, $P < 0.05$, ns (nonsignificant). P , probability of significance.

Table 6
Mean separation of the grain yield (Mg ha^{-1}) of corn grown in Portageville and Clarkton, Missouri, 2007–2009

N rate (kg ha^{-1})	2007 ^a	2008			2009	
	Loam	Loam	Sand	Clay	Loam	Sand
0	3.60c	6.03b	2.04d	1.60e	1.27c	3.81c
45	8.40b	6.02b	3.72c	2.30de	3.10b	6.27b
90	10.94b	8.55ab	4.64bc	3.47bcd	5.81a	7.80ab
134	12.70a	11.27a	5.81a	3.13cd	6.35a	7.81ab
179	12.88a	10.93a	5.36ab	4.62ab	6.78a	8.11a
224	11.42ab	8.95ab	6.13a	5.30a	6.94a	8.62a
269	11.56b	9.29ab	5.73ab	4.13abc	6.85a	9.05a

^aThe small letter indicates the difference within each column for $P = 0.05$. The clay was flooded in 2009 and its yield was erratic.

Discussion

During the 2 years in which the data was taken, the average fresh biomass yield of sweet sorghum ranged from 39 to 91.6 Mg ha^{-1} (Table 7). The sweet sorghum fresh stalk yield ranged from 21.6 to 82.7 Mg ha^{-1} . The dry biomass obtained over the 3 years varied between 11 and 27.5 Mg ha^{-1} (Table 11), which was in agreement with that previously recorded (Soileau and Bradford 1985). The greatest value obtained can be explained by

Table 7
Total fresh biomass (Mg ha^{-1}) of sweet sorghum at Portageville
and Clarkton, Missouri, in 2007–2009

Soil type	2007	2008	2009
Clay		60.65	49.3
Loam	45.59	91.61	39.7
Sand		38.98	46.11

Table 8
Mean separation of sweet sorghum fresh stalk yield (Mg ha^{-1}) at Portageville, and
Clarkton, Missouri, in 2009

N rate (kg ha^{-1})	Soil type		
	Clay	Loam	Sand
0	22.87 c	21.63 c	35.27 c
22	33.76 bc	29.16 bc	38.33 bc
45	37.73 abc	27.88 bc	56.94 a
67	46.05 ab	41.95 a	49.33 ab
90	52.21 a	35.73 abc	39.25 bc
112	53.68 a	41.41 ab	46.2 abc
134	57.56 a	45.68 a	41.10 bc

Notes. The small letter indicates the difference within each column for $P = 0.05$. The impact of N fertilization rate on the stalk yield was significant only in 2009. That year, the stalk yield in the loam soil was the lowest.

Table 9
Water accumulation (Mg ha^{-1}) in sweet sorghum biomass at harvest in Portageville, and
Clarkton, Missouri, 2007–2009

Soil type	Whole biomass (stalk + leaves)			Leaves			Stalk		
	2007	2008	2009	2007	2008	2009	2007	2008	2009
Clay		45.05	34.04		3.81	3.06		41.24	30.98
Loam	29.17	64.16	28.33	2.45	4.03	2.84	26.72	60.12	25.49
Sand		27.94	33.64		1.31	1.48		26.64	32.16

Note. In general, 90–96% of the total water in the biomass was found in the stalk.

the greater fertility of the local soil (1.4%). In Texas, the total dry matter produced by sweet sorghum M81E varied between 11.5 and 15.6 Mg ha^{-1} (Tamang 2010). That yield is less than the 18–32 Mg ha^{-1} as reported by Wu et al. (2010) and the 31.1 Mg ha^{-1} as reported by Prophet and Staggenborg (2010) in Kansas. These differences among studies can be explained by the environment (Tamang 2010).

Table 10

Dry stalk yield response (Mg ha^{-1}) of sorghum to N fertilization in 2009 at Portageville and Clarkton, Missouri

Soil type	N rate (kg ha^{-1})						
	0	22	45	67	90	112	134
Clay	5.82	9.70	10.71	13.90	13.73	15.66	16.17
Loam	6.03	8.24	8.15	11.34	9.86	12.37	14.42
Sand	9.31	9.87	14.52	13.10	10.00	11.40	10.57

Note. The dry stalk yield was four to six times that of the leaves. N fertilization improved the stalk dry yield in 2009.

Table 11

Sweet sorghum dry biomass yield (Mg ha^{-1}) at harvest at Portageville and Clarkton, Missouri, in 2007–2009

Soil type	Dry stalk yield			Dry leaf yield			Total dry biomass		
	2007	2008	2009	2007	2008	2009	2007	2008	2009
Clay		11.78	12.15		3.82	2.55		15.59	14.7
Loam	13.42	22.53	10.4	3.01	4.93	2.24	16.42	27.46	12.64
Sand		9.44	11.13		1.6	1.98		11.04	13.11

Note. The dry biomass yield varied across the years.

In general, results showed that corn grain yield varied between 1.3 and 12.9 Mg ha^{-1} . Other authors have obtained a corn grain yield of 11 Mg ha^{-1} in the US (Heckman et al. 2003).

In general, results showed that N fertilization of sweet sorghum grown after cotton and soybeans had no significant effect ($P > 0.05$) on the biomass yield on the loam and the sandy loam soil. However, on the clay, N fertilization always increased the yield. When grown after corn, sweet sorghum responded to N fertilization on the loam. In contrast to sweet sorghum, corn grain responded to N application ($P < 0.0001$) in the same field where sweet sorghum did not. Many studies already demonstrated the dependence of corn grain yield on N application (Dhugga 2007; Holou and Kindomihou 2011; Holou, Stevens, and Kindomihou 2011). The absence of sweet sorghum biomass response to N fertilization recorded in the present study can be explained by the low N requirement of sweet sorghum. The different responses of sweet sorghum and corn to N application demonstrates the N efficiency of sweet sorghum but also illustrates the need of paying particular attention to the N requirement of sweet sorghum according to the history of the soil. The biomass improvement recorded with the application of N may be generally explained by the involvement of N in many metabolism pathways related to amino, nucleic, and organic acid synthesis and plant growth in general (Holou and Stevens 2012; Zhao et al. 2005, 2003).

Visual observation in the field showed that corn has fewer roots than sorghum, with the shortest roots observed in the clay. In the clay soil, the nodal roots of sweet sorghum were shorter, whereas in the loam soil they were longer and stronger. The change in root architecture can partially explain the different response to N over soil types. Because on the

loam the roots were bigger and longer, nutrients and water uptake from the soil was better, which gave greater biomass yield. This situation can partially explain why the sorghum yield on the clay was very dependent on the N rate. Plant roots were shallow and unable to uptake nutrients and water, and therefore relied on the N provided by the fertilizer. Gallais and Hirel (2004) showed that N uptake by plants can depend on root systems. Furthermore, growing sweet sorghum after soybeans, which produce N, in a rotation system reduced its N need and therefore its response to N (Yamoah, Clegg, and Francis 1998). An investigation in Nebraska (Clegg 1982) showed that N fixation in soybean could account for up to 76 kg N ha⁻¹. An adequate cropping system involving sweet sorghum and soybeans would be a good management practice to reduce the production costs of sorghum. Another factor that can affect the biomass response of sorghum to N is the soil water saturation (Yamoah, Clegg, and Francis 1998). Under dry conditions, the response of sorghum to N was greater than that in wet conditions (Yamoah, Clegg, and Francis 1998). Although sweet sorghum is said to be drought tolerant, to obtain the best biomass yield from it, it is necessary to provide the plant with a sufficient amount of water. Finally, it was recently proven that plants could use proteins as a source of N even without the help of the microorganisms that decompose the proteins (Paungfoo-Lonhienne et al. 2008). They do that by (1) secreting some enzymes into the root environment to digest the proteins in the soil or (2) by directly up taking the proteins in the soil through endocytosis (Paungfoo-Lonhienne et al. 2008). Possibly, sweet sorghum is using a similar mechanism to satisfy its N needs. With that in mind, we can explain the unusual result that sorghum grown on the loam in 2009 responded to N. It was shown that plants could secrete certain proteins through their roots in response to a specific microorganism in their surrounding environments (De-la-Peña et al. 2008). Corn has a high carbon (C)/N ratio. It is known that plant residues that have a high C/N ratio have a slow rate of decomposition (Quemada and Cabrera 1995). This slow decomposition can allow microorganisms in the soil to sequester the N, therefore preventing the plant from taking it up. The immobilization of the N in the soil decreased its availability to plants (Rashid and Voroney 2004). It is possible that the immobilization of N by microorganisms in the loam soil in 2009 changed the microfauna and prevented sweet sorghum from secreting certain proteins that may have helped to improve its N uptake. This situation may have limited the growth of the roots and/or forced sweet sorghum to take the N provided by the fertilizer, explaining why the sorghum grown on the loam soil in 2009 responded to N.

Nitrification is the biological process through which nitrate is produced from ammonium. Nitrification contributes to 70% of the N lost from fertilizer (Subbarao et al. 2009). Several biological nitrification inhibitors were recently found in the root exudates of sorghum, among which the most dominant was sorgoleone (Subbarao et al. 2009, 2008). The biological nitrification inhibitors have the ability not only to prevent nitrification but also to reduce the release of nitrous oxide in the air (Subbarao et al. 2009). The blocking of nitrification can decrease the loss of N and therefore augment the N available to plants for uptake (Subbarao et al. 2006). In contrast to sweet sorghum, undetectable biological nitrification inhibition activity was detected with corn (Subbarao et al. 2009). This finding suggests that corn may use N less efficiently than sweet sorghum. In addition, sweet sorghum can help decrease the amount of nitrous oxides released in the atmosphere. Knowing that the N fertilization rate of corn is very high, the negative environmental impact associated with N fertilization may be worse for corn than for sweet sorghum.

Results showed that the effect of the year on the sweet sorghum biomass production was highly significant ($P < 0.001$). This could be explained by the variation of the weather conditions (Table 3). The difference between the soil types may be explained by their

mineral composition and structure (Table 2). The biomass yield was poor in the clay soil, probably because of the fine structure of that soil and the lack of oxygen that reduced the growth of the roots. The fact that in 2009, early flooding affected the growth of corn in contrast to that of sweet sorghum suggested that sweet sorghum may be apparently a sturdier plant and can stand the flooding better than corn. This suggested that sweet sorghum could produce better biomass on clay even under flooding conditions, which are more detrimental to corn. Based on the present data, sweet sorghum can be cultivated on marginalized soil for biofuel production where corn would fail. Over the years, the selective breeding of corn has improved its yield by 50–60% (Duvick and Cassman 1999), suggesting that with time, the breeding of sweet sorghum can potentially increase its biomass yield. The breeding of short sweet sorghum hybrids with high sugar production will be highly important to avoid lodging and facilitate harvest. That was successfully done with grain sorghum and may be achieved with sweet sorghum as well.

Conclusion

Results showed that the biomass yield from corn and sweet sorghum was dependant on the soil and the N fertilization. In general, N fertilization of sweet sorghum grown after cotton and soybeans had no significant effect on the biomass yield on loam and sand. However, in the clay, N fertilization consistently increased sweet sorghum yield. When grown after corn, sweet sorghum responded to N fertilization in the loam soil. We also observed that corn responded to N rate in the same field that sweet sorghum did not, suggesting that sweet sorghum may have other mechanisms to uptake N from the soil. Sweet sorghum roots system and biological nitrification inhibitors may play a significant role in its response to N fertilization. The analysis of the nutrient removal, the sugar yield, and the potential ethanol yield obtained under each N rate will give complementary support to whether it is necessary to fertilize sweet sorghum when growing it for biofuel production feedstock. It is likely, under certain conditions, such as in very poor soil, sweet sorghum will require N application before achieving its maximum productivity. Other nutrients may also be required. Also, in order to keep the soil at its initial fertility instead of degrading it, a minimum N rate of fertilization will be required for sweet sorghum. This minimal N recommendation will certainly depend not just on the initial soil fertility or the N uptake by sweet sorghum but also on which part of the biomass is removed from the field during harvest. For instance, nutrient removal will vary whether the entire sweet sorghum biomass is removed from the field, or whether just the stalk or just the juice will be removed. In general 67 kg N ha⁻¹ was the optimum N rate to maximize sweet sorghum biomass whereas a minimum of 134 kg N ha⁻¹ was required to reach the maximum corn grain yield.

References

- Almodares, A., M. R. Hadi, and H. Ahmadpour 2008. Sorghum stem yield and soluble carbohydrates under different salinity levels. *African Journal of Biotechnology* 7:4051–4055.
- Amanullah, P. 2010. Timing and rate of nitrogen application influence grain quality and yield in maize planted at high and low densities. *Journal of the Science of Food and Agriculture* 90:21–29.
- Balat, M. 2007. An overview of biofuels and policies in the European union. *Energy Sources, Part B: Economics, Planning and Policy* 2:167–181.
- Berndes, G., M. Hoogwijk, and R. Van Den Broek. 2003. The contribution of biomass in the future global energy supply: A review of 17 studies. *Biomass and Bioenergy* 25:1–28.

- Binder, D., D. Sander, and D. Walters. 2000. Maize response to time of nitrogen application as affected by level of nitrogen deficiency. *Agronomy Journal* 92:1228–1236.
- Bolck, B. R. 1984. Efficient use of nitrogen in cropping systems. In *Nitrogen crop production*, ed. R. D. Hauck, 273–294. Madison, Wisc.: American Society of Agronomy.
- BP G. 2006. *BP statistical review of world energy*. London: BP Global.
- Bray, R., and L. Kurtz. 1945. Determination of total organic and available forms of phosphorus in soil. *Soil Science* 59:39–45.
- Brown, J., and R. Rodriguez. 1983. *Soil testing in Missouri: A guide for conducting soil tests in Missouri* (Cooperative Extension Bulletin EC923). Columbia, Mo.: University of Missouri, Columbia.
- Clegg, M. D. 1982. Effect of soybean on yield and nitrogen response of subsequent sorghum crops in eastern Nebraska. *Field Crops Research* 5:233–239.
- Crutzen, P., and D. Ehhalt. 1977. Effects of nitrogen fertilizers and combustion on the stratospheric ozone layer. *Ambio* 6:112–116.
- Crutzen, P. J., A. R. Mosier, K. A. Smith, and W. Winiwarter. 2007. N₂O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics Discussions* 7:11191–11205.
- De-la-Peña, C., Z. Lei, B. S. Watson, L. W. Sumner, and J. M. Vivanco. 2008. Root–microbe communication through protein secretion. *Journal of Biological Chemistry* 283:25247–25255.
- Dhugga, K. S. 2007. Maize biomass yield and composition for biofuels. *Crop Science* 47:2211–2227.
- Duvick, D. N., and K. G. Cassman. 1999. Post–green revolution trends in yield potential of temperate maize in the north-central United States. *Crop Science* 39:1622–1630.
- Energy, I. A. 2007. *Annual energy outlook 2007 with projections to 2030*. Washington, D.C.: U.S. Department of Energy.
- English Jr., G., and T. W. Ewing. 2002. *Vision for bioenergy and biobased products in the United States* (Biomass Research and Development Technical Advisory Committee). Washington, D.C.: USDOE, USDOT, USEPA, USDA.
- Gallais, A., and B. Hirel. 2004. An approach to the genetics of nitrogen use efficiency in maize. *Journal of Experimental Botany* 55:295–306.
- Gnansounou, E., A. Dauriat, and C. E. Wyman. 2005. Refining sweet sorghum to ethanol and sugar: Economic trade-offs in the context of North China. *Bioresource Technology* 96:985–1002.
- Halvorson, A. D., F. C. Schweissing, M. E. Bartolo, and C. A. Reule. 2005. Corn response to nitrogen fertilization in a soil with high residual nitrogen. *Agronomy Journal* 97:1222–1229.
- Hawkins, J., J. Sawyer, D. Barker, and J. Lundvall. 2007. Using relative chlorophyll meter values to determine nitrogen application rates for corn. *Agronomy Journal* 99:1034.
- Heckman, J. R., J. T. Sims, D. B. Beegle, F. J. Coale, S. J. Herbert, T. W. Bruulsema, and W. J. Bamka. 2003. Nutrient removal by corn grain harvest. *Agronomy Journal* 99:1034–1040.
- Holou, R., and V. Kindomihou. 2011. Impact of nitrogen fertilization on the oil, protein, starch, and ethanol yield of corn (*Zea mays* L.) grown for biofuel production. *Journal of Life Sciences* 5:1013–1021.
- Holou, R., and G. Stevens. 2012. Juice, sugar, and bagasse response of sweet sorghum (*Sorghum bicolor* (L.) Moench cv. M81E) to N fertilization and soil type. *Global Change Biology Bioenergy* 4:302–310.
- Holou, R. A. Y., G. Stevens, and V. Kindomihou. 2011. Impact of nitrogen fertilization on nutrient removal by corn grain. *Crop Management* 10.1(2011). doi:10.1094/CM-2011-1223-02-RS.
- Kahabka, J., H. Van Es, E. McClenahan, and W. Cox. 2004. Spatial analysis of maize response to nitrogen fertilizer in central New York. *Precision Agriculture* 5:463–476.
- Karp, A., and I. Shield. 2008. Bioenergy from plants and the sustainable yield challenge. *New Phytologist* 179:15–32.
- Keeney, D. R., and T. H. Deluca. 1992. Biomass as an energy source for the midwestern US. *American Journal of Alternative Agriculture* 7:137–143.
- Lorenz, D., and D. Morris. 1995, August. *How much energy does it take to make a gallon of ethanol?* Washington D.C.: Institute for Local Self Reliance (ILSR).

- Monti, A., and G. Venturi. 2003. Comparison of the energy performance of fibre sorghum, sweet sorghum, and wheat monocultures in northern Italy. *European Journal of Agronomy* 19:35–43.
- Netondo, G., J. Onyango., and E. Beck. 2004. Sorghum and salinity, I: Response of growth, water relations, and ion accumulation to NaCl salinity. *Crop Science* 44:797–805.
- Patzek, T. W. 2006. A statistical analysis of the theoretical yield of ethanol from corn starch. *Natural Resources Research* 15:205–212.
- Paungfoo-Lonhienne C., T. G. A. Lonhienne, D. Rentsch, N. Robinson, M. Christie, R. I. Webb, H. K. Gamage, B. J. Carroll, P. M. Schenk, and S. Schmidt. 2008. Plants can use protein as a nitrogen source without assistance from other organisms. *Proceedings of the National Academy of Sciences of the United States of America* 105:4524–4529.
- Pimentel, D. 1991. Ethanol fuels: Energy security, economics, and the environment. *Journal of Agricultural and Environmental Ethics* 4:1–13.
- Pimentel, D. 2001. The limits of biomass energy. In Meyers, R. A. (ed.), *Encyclopedia of Physical Science and Technology*, Vol. 2., 3rd ed., San Diego: Academic, pp. 159–171.
- Propheter, J. L., and S. Staggenborg. 2010. Performance of annual and perennial biofuel crops: Nutrient removal during the first two years. *Agronomy Journal* 102:798–805.
- Quemada, M., and M. Cabrera. 1995. Carbon and nitrogen mineralized from leaves and stems of four cover crops. *Soil Science Society of America Journal* 59:471–477.
- Rashid, M., and R. Voroney. 2004. Land application of oily food waste and corn production on amended soils. *Agronomy Journal* 96:997–1004.
- Rashid, M., and R. Voroney. 2005. Nitrogen fertilizer recommendations for corn grown on soils amended with oily food waste. *Journal of Environmental Quality* 34:2045–2051.
- Ruiz Diaz, D., J. Hawkins, J. Sawyer, and J. Lundvall. 2008. Evaluation of in-season nitrogen management strategies for corn production. *Agronomy Journal* 100:1711–1719.
- Ruser, R., R. Schilling, H. Steindl, H. Flessa, and F. Beese. 1998. Soil compaction and fertilization effects on nitrous oxide and methane fluxes in potato fields. *Soil Science Society of America Journal* 62:1587–95.
- Saxton, A. M. 1998. A macro for converting mean separation output to letter groupings in Proc. Mixed, pp. 1243–1246. In *Proceedings, 23rd SAS Users Group International*, 22–25 March 1998, Nashville, TN. Cary, NC: SAS Institute.
- Scharf, P., W. Wiebold, and J. Lory. 2002. Corn yield response to nitrogen fertilizer timing and deficiency level. *Agronomy Journal* 94:435–441.
- Schepers, J. S., M. G. Moravek, E. E. Alberts, and K. D. Frank. 1991. Maize production impacts on groundwater quality. *Journal of Environmental Quality* 20:12–16.
- Shapouri, H., J. A. Duffield, M.S. Graboski. 1995. Estimating the Net Energy Balance of Corn Ethanol. Washington, DC: U.S. Department of Agriculture, Economic. Research Service, AER-721.
- Shapouri, H., J. Duffield, and M. Wang. 2002. *The energy balance of corn ethanol: An update*. Washington, D.C.: National Agricultural Library.
- Sipos, B., J. Réczey, Z. Somorai, Z. Kádár, D. Dienes, and K. Réczey. 2009. Sweet sorghum as feedstock for ethanol production: Enzymatic hydrolysis of steam-pretreated bagasse. *Applied Biochemistry and Biotechnology* 153:151–162.
- Soileau, J., and B. Bradford. 1985. Biomass and sugar yield response of sweet sorghum to lime and fertilizer. *Agronomy Journal* 77:471–475.
- Spiertz, J. H. J., and F. Ewert. 2009. Crop production and resource use to meet the growing demand for food, feed and fuel: Opportunities and constraints. *NJAS - Wageningen Journal of Life Sciences* 56:281–300.
- Storer, D. 1984. A simple high sample volume ashing procedure for determination of soil organic matter. *Communications in Soil Science and Plant Analysis* 15:759–772.
- Subbarao, G., O. Ito, K. Sahrawat, W. Berry, K. Nakahara, T. Ishikawa, T. Watanabe, K. Suenaga, M. Rondon, and I. Rao. 2006. Scope and strategies for regulation of nitrification in agricultural systems—Challenges and opportunities. *Critical Reviews in Plant Sciences* 25:303–335.

- Subbarao, G., M. Kishii, K. Nakahara, T. Ishikawa, T. Ban, H. Tsujimoto, T. George, W. Berry, C. Hash, and O. Ito. 2009. Biological nitrification inhibition (BNI)—Is there potential for genetic interventions in the Triticeae? *Breeding Science* 59:529–545.
- Subbarao, G. V., K. Nakahara, T. Ishikawa, T. Yoshihashi, O. Ito, H. Ono, M. Ohnishi-Kameyama, M. Yoshida, N. Kawano, and W. L. Berry. 2008. Free fatty acids from the pasture grass *Brachiaria humidicola* and one of their methyl esters as inhibitors of nitrification. *Plant and Soil* 313:89–99.
- Tamang, P. 2010. *Nitrogen fertilizer requirements for ethanol production from sweet and photoperiod sensitive sorghums in the Texas southern high plains*. Lubbock, Texas: Texas Tech University.
- Tesso, T., L. Claflin, and M. Tuinstra. 2005. Analysis of stalk rot resistance and genetic diversity among drought-tolerant sorghum genotypes. *Crop Science* 45:645–652.
- Thomas, G. 1982. Exchangeable cations. In *Methods of soil analysis, part 2: Chemical and microbiological properties*, ed. A. Page, R. Miller, and D. Keeney, 160–161. Madison, Wisc.: ASA.
- Tsuchihashi, N., and Y. Goto. 2004. Cultivation of sweet sorghum (*Sorghum bicolor* (L.) Moench) and determination of its harvest time to make use as raw material for fermentation, practiced during rainy season in dry land in Indonesia. *Plant Production Science* 7:442–448.
- Vitousek, P., J. Aber, R. Howarth, G. Likens, P. Matson, D. Schindler, W. Schlesinger, and G. Tilman. 1997. Human alteration of the global nitrogen cycle: Causes and consequences. *Ecological Applications* 7:737–750.
- Woodruff, C. 1967. Crop response to lime in the midwestern United States. In *Soil acidity and liming*, ed. R. W. Pearson and F. Adams, 207–231. Madison, Wisc.: ASA.
- Wu, X., S. Staggenborg, J. L. Prophet, W. L. Rooney, J. Yu, and D. Wang. 2010. Features of sweet sorghum juice and their performance in ethanol fermentation. *Industrial Crops and Products* 31:164–170.
- Wullschleger, S. D., E. B. Davis, M. E. Borsuk, C. A. Gunderson, and L. R. Lynd. 2010. Biomass production in switchgrass across the United States: Database description and determinants of yield. *Agronomy Journal* 102:1158–1168.
- Yamoah, C., M. Clegg, and C. Francis. 1998. Rotation effect on sorghum response to nitrogen fertilizer under different rainfall and temperature environments. *Agriculture, Ecosystems and Environment* 68:233–243.
- Zhao, D., K. Reddy, V. Kakani, and V. Reddy. 2005. Nitrogen deficiency effects on plant growth, leaf photosynthesis, and hyperspectral reflectance properties of sorghum. *European Journal of Agronomy* 22:391–403.
- Zhao, D., K. Raja Reddy, V. Kakani, J. Read, and G. Carter. 2003. Corn (*Zea mays* L.) growth, leaf pigment concentration, photosynthesis, and leaf hyperspectral reflectance properties as affected by nitrogen supply. *Plant and Soil* 257:205–218.
- Zuurbier, P., and J. van de Vooren. 2008. *Sugarcane ethanol: Contributions to climate change mitigation and the environment*. Wageningen, the Netherlands: Wageningen Academic.