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Sweet sorghum ethanol yield component response to nitrogen fertilization

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ABSTRACT

Increasing demand for high-yielding, alternative biofuel feedstocks elicits the need to fully understand sweet sorghum (*Sorghum bicolor* (L.) Moench) yield response to varying nitrogen (N) fertilization rates in the U.S. Midwest. The objective of this three-year study was to determine the optimum N fertilization rates for the production of two common sweet sorghum cultivars (Dale and Top 76-6) in central Missouri. Five N rates (0, 56, 112, 168, 224 kg N ha^{-1}) were imposed and tested for their effects on dry matter yield, stem juice yield, Brix, fermentable sugar yield, theoretical juice ethanol yield, theoretical lignocellulosic ethanol yield, and total theoretical ethanol yield. Except for Brix, N treatment significantly influenced all yield parameters in all three years. The two varieties yielded similarly across most measured parameters. Total dry matter yields averaged 16.8 Mg ha^{-1}, juice yields averaged 9113 L ha^{-1}, and fermentable sugar yields averaged 1055 kg ha^{-1} across years and varieties. Total ethanol yields averaged 7488 L ha^{-1} and were highest at 168 kg N ha^{-1} across the three years, indicating that sweet sorghum in Missouri may reach maximum yields near that fertilization rate. Annual precipitation and temperature differences greatly influenced dry matter, stem juice, and sugar yields, thereby affecting theoretical ethanol yields, such that yields were lower in years with less rainfall and lower temperatures, which also limited the N response in these years.

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1. Introduction

Nitrogen fertilization of bioenergy crops is often considered the greatest single expense incurred by producers, accounting for 15–35% of production costs (Amosson et al., 2011; Linton et al., 2011). Excessive use of N fertilizer contributes to greenhouse gas emissions, raises crop production costs, and limits the transition of biofuel feedstocks from net fuel sinks to net fuel sources (Putnam et al., 1991). Thus, determination of N fertilizer requirements that optimize yield while minimizing costs and N losses is critical from both an economic and environmental perspective.

Sweet sorghum (*Sorghum bicolor* (L.) Moench) is a C4 annual grass species known for high water use efficiency and high N use efficiency (Gardner et al., 1994). Sweet sorghum is considered to be drought tolerant (Propheter et al., 2010) and has exhibited flood tolerance (Houx et al., 2013; Promkhambut et al., 2011), and therefore could be grown on marginal cropland less suitable for maize (*Zea mays* L.) or soybean (*Glycine max* (L.) Merr.) production. With large amounts of fertilizer applications, sweet sorghum has the potential to yield 20–40 Mg ha^{-1} DM (Propheter et al., 2010; Turhollow et al., 2010), but lower yields have been observed in Missouri (Holou and Stevens, 2012). Houx and Fritschi (2013) reported that, in central Missouri, N rates as low as 56 kg ha^{-1} can achieve 10.1 Mg ha^{-1} DM and theoretical ethanol yields of more than 5000 L ha^{-1}, demonstrating considerable potential for ethanol production from sweet sorghum even with a later planting date and low N fertilizer input.

Published research on the response of sweet sorghum to N fertilization reveals considerable variation in optimum N rates across studies. Wiedenfeld (1984) observed that stem sugar quality and theoretical juice ethanol yield of sweet sorghum grown in Texas was maximized with 112 kg N ha^{-1} and that both traits decreased with higher N rates. More recently, Tamang et al. (2011) reported optimum N fertilizer application for ethanol production to be between 59–101 kg N ha^{-1} in Texas. In contrast, Almodares et al. (2007), recorded DM and stem sugar yield increases with N rates up to 200 kg ha^{-1}. In the U.S. Midwest, N fertilization responses of sweet sorghum varies considerably. Putnam et al. (1991) reported DM yields of 20–25 Mg ha^{-1} and total fermentable carbohydrate yields of 6700 kg ha^{-1} in response to 179 kg N ha^{-1} in Minnesota. In Iowa, sweet sorghum consistently produced high DM with 140 kg N ha^{-1} (Hallam et al., 2001), while no significant

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effect of N treatments ranging from 0 to 90 kg ha^{-1} N were observed in Nebraska (Wortmann et al., 2010). Holou and Stevens (2012) observed optimum juice, sugar, and DM yields with applications of only 67 kg N ha^{-1} in southeast Missouri.

The differences across these studies suggest important environmental influences on sweet sorghum responses to N fertilization and illustrate the need for optimization to local environments. Further, understanding the relationship between different N fertilizer rates and sweet sorghum yields for ethanol production is an important step toward greater fertilizer-use efficiency, minimizing inputs in bioenergy feedstock systems, and consequently sustainable sweet sorghum production. While extensive data exist for yields of several biofuel feedstocks, including sweet sorghum, there are few available studies on the yield response to different N application rates in the lower Midwest for this crop. The objective of this study was to determine the influence of five N fertilization rates on sweet sorghum bagasse DM production, stem juice yield (SJY), juice °Brix (Brix), fermentable sugar yield (FSY), juice ethanol yield (JEY), lignocellulosic ethanol yield (LEY), and total ethanol yield (TEY).

2. Materials and methods

2.1. Site description, weather, and crop management

This study was conducted at the Bradford Research Center (BRC) in central Missouri (38′ 53″ N; 92′ 12″ W) on a Mexico silt loam (fine, smectitic, mesic, Vertic Epiaqualf) soil from 2009 through 2011. Thirty year (1983–2012) average temperature and annual precipitation at BRC are 12.8 °C and 1145 mm respectively, and were recorded on-farm and accessed through the Missouri Agricultural Weather Database (2012).

The experiment included five N treatments (0, 56, 112, 168, and 224 kg N ha^{-1}) and two public sweet sorghum varieties ('Dale' and 'Top 76-6′) arranged in four replications. Nitrogen treatment main plots were arranged in randomized complete blocks and sweet sorghum varieties were subplots arranged as strips within replication. Main plots were 12 rows wide and 15 m long and subplots were six rows wide and 15 m long. The same field and plot design was used for the three study years with no crop rotation, and the field was tilled with a disk to a depth of approximately 0.15 m prior to each planting Sweet sorghum varieties were sown in 0.76 m rows, 0.02 m deep, with an approximate population of 208,000 plants ha^{-1} on June 7, 2009 and on June 18, 2010. In 2011 a similar early-June planting occurred, but a hailstorm on 13 June damaged the early crop, prompting a 23 June replant which resulted in a shorter growing season.

Nitrogen treatments were chosen such that they encompassed the broad range of N treatments previously reported to maximize sweet sorghum yields in different environments (see Section 1), and also considering a high rate to match a N fertilizer rate for the production of high corn yields in Missouri. To span the broad range, N rate increments of 56 kg N ha^{-1} were selected. Nitrogen was broadcast applied each year as SuperU urea (Koch Fertilizer, Wichita, KS). The 56 and 112 kg N ha^{-1} treatments were applied as single applications at planting and the 168 and 224 kg N ha^{-1} treatments were split-applied with 112 kg ha^{-1} applied at planting and the remaining N applied approximately two weeks after seedling emergence to reduce supposed N fertilizer losses. Hereafter, the N treatments will be referred to as 0N, 56N, 112N, 168N, and 224N.

Harvests were conducted shortly after the first killing frost, when sweet sorghum was in the hard dough to soft dough stages. Plants from a 2 m long row-section were cut to a stubble height of 0.05 m on 8 October, 2009, 28 October 2010, and 20 October 2011, and processed immediately. Fresh weight was determined and three representative plants were selected for further processing. The three-plant subsample was weighed and panicles removed prior to crushing of the three stems to extract stem juice. In 2009, samples were crushed with a small hand-powered roller press, and in 2010 and 2011, samples were crushed with a three-roller sugarcane press, with similar extraction efficiencies regardless of press. Stem juice was collected, strained through cheesecloth, and volume and weight were recorded to calculate SJY. Juice sugar concentrations were estimated by Brix with an r^2 mini handheld refractometer (Reichert Technologies, Inc., Buffalo, NY) from the stem juice sample immediately after crushing. The average Brix reading of two 1.0 mL aliquots of stem juice sample was used for data analysis. Bagasse was dried in a forced-air drier at 55 °C until weights stabilized and weights were recorded. The three-plant subsample fresh weights before and after juce extraction, dry weights of the crushed plants (bagasse), juice weight and Brix were applied to the 2-m sample and used to calculate yields.

While not a direct measure of sugar, using Brix to calculate fermentable sugar content has been shown to correlate well to HPLC methods (Guigou et al., 2011). Common conversion calculations were used to estimate FSY, JEY, and LEY. Brix readings were multiplied by SJY to calculate total FSY, assuming that sugars equaled 75% of Brix (Putnam et al., 1991; Wortmann et al., 2010). Theoretical JEY was calculated as 1.76 kg sugars L^{-1} ethanol, assuming 80% conversion efficiency (Putnam et al., 1991; Smith et al., 1987). This equation closely mirrors results from laboratory ethanol conversion (Bunphan et al., 2015). To estimate bagasse LEY, a conversion of 415 L EtOH Mg^{-1} DM bagasse was used according to Li et al. (2013).

2.2. Statistical analysis

Two separate analyses are presented. First, to analyze dependent variables within years, analysis of variance (ANOVA) was performed with PROC MIXED (SAS Institute, 2008) with replication and all interactions with replication as random effects. This analysis allowed for a presentation and discussion of the different N rate effects within years. Since no N treatment × cultivar interactions were identified for all traits but Brix, yields of the two varieties were pooled within each year and means presented and discussed for each yield parameter. However, for Brix, data are presented by cultivar. Second, the aforementioned ANOVA was run with years, replication, and all interactions with replication as random effects to create N rate means across years. This analysis was conducted to better define an N rate that would be more precise representative across years with contrasting environmental and management conditions that affect sweet sorghum response to N fertilization. In essence, the intent of the second analysis was to determine the consistency of sweet sorghum response to N fertilization across multiple years. Treatment means were compared for each analysis by issuing CONTRAST statements within PROC MIXED to create custom hypothesis testing for each N rate at $P = 0.05$ significance level. Dependent variables included total DM, SJY, Brix, FSY, JEY, LEY, and TEY. PROC CORR was used to identify correlations between yield variables.

3. Results

Analysis of variance across all three years revealed significant year effects for all measured traits (Table 1). This was not surprising, considering the observed differences in precipitation among the three growing seasons (Table 2). With the exception of Brix, N treatment affected all measured traits. The response to N fertilizer treatment differed from year to year only for DM and Brix. Significant variety effects were observed for Brix, FSY, and JEY but not for any of the other traits. No significant N treatment × variety

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