THE EFFECTS OF NITROGEN FERTILIZATION ON BIOENERGY SORGHUM YIELD AND QUALITY

A Thesis

by

SZILVIA KATALIN ZILAHI-SEBESSS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2012

Major Subject: Agronomy

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Chair of Committee,	Jürg M. Blumenthal
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ABSTRACT

The Effects of Nitrogen Fertilization on Bioenergy Sorghum Yield and Quality.

(May 2012)

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Chair of Advisory Committee: Dr. Jürg M. Blumenthal

Forage sorghum (Sorghum bicolor L. Moench) is one of the prospective crops that may be used to produce biofuels in the future. Therefore, it is of interest to find management practices that improve both the production of biomass yield and quality. This study presents observations of the effects different rates of nitrogen fertilization have on yield, tissue nitrogen content, and tissue quality measures such as ash, lignin, sucrose, xylans, cellulose and starch content, based on three years of field trials from the Brazos Bottom and one year of field trials from near China, Texas. Data for the quality components were obtained using near infrared spectroscopy, with the exception of tissue nitrogen which was determined by using the dry combustion method. This study has showed fertilizer nitrogen had a strong positive correlation with the tissue nitrogen of sorghum biomass. Changes in tissue quality in relationship with fertilizer nitrogen levels and tissue nitrogen concentration were also observed. Ash showed a strong positive and sucrose showed a strong negative correlation to both

tissue nitrogen concentration and fertilizer nitrogen application. Similarly to sucrose, starch also decreased with higher nitrogen levels and lignin was found to increase slightly. The concentration of cellulose and xylans were very weakly affected by nitrogen application and nitrogen concentration.

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INTRODUCTION

The Energy Independence and Security Act of 2007 called for a minimum of 36 billion gallons of renewable fuel by 2022. To reach this goal, ligno-cellulosic biofuel feedstocks must be included as biofuel sources in addition to corn grain. The Biomass Program has been focused on enabling research and development to make cellulosic ethanol cost-competitive with corn based ethanol (US Department of Energy, 2010). It is envisioned that transportation fuel from biomass will be 10% in 2020 and 20% in 2030 of the total transportation fuel consumption (Perlack et al., 2005). Sorghum is one of the crops that could possibly be used as a biofuel feedstock. The goal is to achieve the highest yield and quality with the lowest energy input, and the least impact on the environment. Fertilization adds extra cost and overall energy expenditure to the production process. Nitrogen is the element that is usually the most limiting for crops, therefore supplementing growth with nitrogen fertilizers is usually necessary for economic sustainability. For this reason it is important to find how nitrogen fertilizer can most effectively be used. Since sorghum is widely used for animal feed, its digestibility has been extensively studied. However when it comes to using sorghum as a biofuel

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feedstock, the quality measures can be somewhat different from what is measured for digestibility depending on the conversion process. For example, while lignin content would be of interest from both a feed quality standpoint and a bioethanol conversion standpoint, ash is a main concern of thermochemical conversion processes but not generally considered when describing digestibility. Nitrogen fertilization and changes in tissue nitrogen concentration might affect the quality components that would influence the efficiency at which sorghum biomass can be converted to biofuels.

LITERATURE REVIEW

Sorghum: its uses and origins, and current place in the US economy

Sorghum bicolor L. Moench originates from the tropical regions of Africa and has been cultivated for thousands of years (US Grains Council 2005). It is a popular foodcrop in Africa, the Middle East and India. The grain can be cooked whole in dishes or milled into flour for baking and cooking. There are also sweet sorghum varieties which are not grown for their grain, rather for the sugar content found in the juice in their stems. Sweet sorghum is cultivated for making sorghum syrup and for animal feed. There are also sorghum varieties which are photoperiod sensitive and are primarily grown for green forage. These varieties do not flower outside of the tropical regions, therefore they keep growing as long as the weather permits and can reach heights of up to 6 meters. Their sugar content is not as high as the sweet sorghums', but they produce a large amount of biomass. Sorghum was introduced to the United States in the 17th century and gained popularity by the 1850s. At first it was grown mainly for the sugar, but later farmers realized that due to its adaptability to less than optimum conditions it can substitute, corn in some areas and grain sorghum gained dominance over the sweet varieties (Undersander et al 1990).

In 2010, sorghum was planted on approximately 4.8 million acres. Texas is among the top five sorghum producing states along with Kansas, Oklahoma, Colorado and South Dakota (Sorghum Chekoff 2011). Grain sorghum is a possible option for biofuel production because the starch in the grain can be used for ethanol distillation similar to corn. However, the forage sorghum types might even be a better option in the future since they produce more biomass per hectare which is a great advantage in case the conversion process allows for the entire biomass to be used. Currently, forage sorghum is grown for the purpose of animal feeding, but it is a viable option for use as a lignocellulosic biofuel feedstock. Sweet sorghum varieties could effectively be used in simple fermentation processes as well just like juice from sugarcane or starch from corn kernels.

Sorghum as a potential biofuel crop

Sorghum is a very resilient crop as it grows well under environmental stresses such as drought (Tesso et al 2005). In more arid areas, it could replace corn as a biofuel feedstock. Sorghum is often grown in areas that would not be as profitable for corn or soybean. Probably because of its African origins and because of its extensive root system, sorghum tolerates drought better than other C4 crops, and it also tolerates low levels of soil salinity better than corn and sugarcane (Almodares and Hadi 2009). In Texas near Amarillo, corn reached lower yields when it was irrigated equally to sorghum (Bean and McCollum 2006). One study even went as far as to state that irrigation affected sorghum yield significantly, but not the total amount of sucrose obtained per hectare. Averaged over two years and two locations, one with and the other without irrigation, their results showed that even though green yield was significantly higher in the irrigated location, the total sugar yields and estimated ethanol yields did not significantly differ from each other (Smith and Buxton 1993). For this reason sorghum could fill the gaps by stepping into biomass production for biofuel where corn and soybean does not perform well.

Sweet sorghum is also often compared to sugarcane in its characteristics of having high sugar content in the juice of the stem. Sugarcane is a major biofuel crop currently in use in Brazil. However in the US, sweet sorghum could be a good alternative to sugarcane since sorghum is planted from seed and is generally grown as an annual crop. This is an advantage over switchgrass and some other perennial species as well since this makes sorghum highly adaptable to market demands, and depending on the climate, it can be harvested up to three times a year.

Ethanol production and ethanol yield

Forage sorghum can be a feedstock for both fermentation and thermochemical processes like gasification and pyrolysis. The sweet varieties can have their sucrose content easily converted to ethanol by microbial processes. The photoperiod sensitive varieties which do notaccumulate as much sugar as the sweets, but produce large biomass yield, may be a better feedstock for thermochemical conversion, but could also be a feedstock for producing ethanol from cellulose and hemicellulose with the help of new enzymatic and microbiological processes. Currently, the only biofuel production on a large industrial scale in operation is limited to corn grain distillation (US Department of Energy, 2010), but other options of feedstocks and conversion methods are also being tested and developed for economic profitability. What would be the main method of converting sorghum biomass to biofuels in the future is not yet known, therefore when looking at feedstock quality we must consider all the possible options. In case the main route will be microbial conversion, then a low amount of lignin and a large amount of simple carbohydrates will be desirable. In this process, lignin is not only an inert indigestible material, but will also lower conversion efficiency of other carbohydrates (Lorenz 2009). If, however, thermochemical conversion would turn out to be more feasible than fermentation, then a dense biomass with high lignin and structural carbohydrates would be a better option for higher energy yields. For fermentation, another problem that has been prevalent in converting biomass is the presence of 5-carbon sugars. Most commercially available yeasts are not able to convert them. Xylose which is a component of hemicellulose also carries energy and developing yeasts and bacteria that would convert it have yielded successful results (NREL, 1995) but having to add these genetically modified microorganisms will likely increase cost. Therefore, the concentration of xylans in the biomass can also be considered a component of feedstock quality which might later influence the profitability of conversion.

Thermochemical conversion

It is also possible to put sorghum biomass through a thermochemical conversion process such as gasification or pyrolysis. These processes use considerable energy, but their advantage is that the entire biomass is used and no expensive enzyme complexes are needed (Munasinghe and Khanal, 2010). During pyrolysis the biomass is anaerobically decomposed due to high temperatures and the main end product is bio-oil, which can be used as a fuel, and biochar is produced as a byproduct (US Department of Energy, 2005). Syngas is produced in a different process called gasification, where the biomass is broken down to carbon monoxide and hydrogen using a mixture of oxygen and steam at high temperatures. Syngas can itself be used as a fuel but can also be converted to methanol (Hanelinck and Faaij, 2005). Any organic material can be converted by these methods regardless of their carbohydrate composition. Organic material composed of high energy compounds would be more preferential for better energy output. Therefore, biomass high in lignin and structural carbohydrates would be preferred. There is one component of organic material that is not convertible in these processes and in fact cause problems at high temperatures. This component is ash which consists of metals and inorganic salts. At high temperatures these inorganic residues will agglomerate and melt (Cheney and Baker, 2006), and if not dealt with can cause damage to the equipment. We found that the concentration of ash in dry sorghum biomass ranged from 3 to almost 10% by weight. In any process, this is a significant amount of material that can not be converted to energy. Therefore, the concentration of ash is another feedstock quality worth taking into consideration when choosing management practices.

Nitrogen effect on yield

To be profitable, it is important to establish what the optimum rates of fertilization are for any crop. Nitrogen is an element that is taken up in the largest quantities and that crops tend to be most limited for. For this reason, the cost of nitrogen fertilizer is an important factor when aiming to maximize biomass quanitity and quality at the lowest cost. Yield varies widely from region to region also. According to USDA statistics average yearly silage sorghum yield ranged between 9.6 to 13.8 Mg ha^{-1} between 1996 and 2008 in the USA (USDA, 2009, Agricultural Statistics, Table 1-62). In the cold northern climate of Delhi, Canada maximum yield was reported to be around 6 Mg ha^{-1} (Beyaert and Roy 2005), whereas a study in El Reno, Oklahoma reported 27 Mg ha^{-1} average yield from a single late season harvest (Venuto and Kindiger, 2007). Nitrogen requirements for forage sorghum are generally thought to be relatively low. At 218 and 291 kg N ha^{-1} for conventional forage sorghum varieties and

106 to 140 kg ha^{-1} for brown midrib varieties, a study in New Mexico found no nitrogen response at these nitrogen rates (Marsalis et al 2009). One reason may have been that these rates were at or above that required for achieving maximum yield in that area. In northern Italy with average yields of around 20 Mg ha^{-1}, there similarly was no yield response to nitrogen fertilization on a soil that already had a high amount of nitrates (Barbanti, 2006). In this same study, they also found no strong relationship between nitrogen rate and tissue nitrogen concentration, probably for the above mentioned reason. However, in a study by Beyaert and Roy (2005), they found that maximum yield could be established at 125 kg N ha^{-1} and the most economic rates were around 83 to 107 kg ha^{-1}. In Fort Valley, Georgia, where two nitrogen rates were used along with different tillage methods and covercrops, it was found that using 60-65 kg N ha^{-1} gave higher yields than using no fertilizer and this rate was more economical than using the higher rate of 120-130 kg N ha^{-1} (Sainju, 2006). At Hohenheim Germany, the highest yield was achieved by a split application of two times 45 kg N ha^{-1} (Eghbal, 1993) and at Isfahan, Iran highest total dry weight was achieved by the application of 75 kg N and 25 kg K ha^{-1} (Almodares et al., 2006). This also shows that when looking at fertilization effects, one must make sure the plants are not limited for other nutrients as this could change the yield and quality response of the crop. Therefore, when looking for a yield response many factors should be considered like climate, varieties used, soil type, nitrogen application method, residual nitrogen in the soil, or the availability of water.

When nitrogen is abundant in the soil, it has been observed that the tissue nitrogen concentration of plants increases. According to a study done on arctic vegetation, luxury consumption of nitrogen was postulated to be a form of competition (Van Wijk et al., 2003). The increase of tissue nitrogen concentration can not necessarily be considered luxury consumption unless this increase in nitrogen concentration manifests itself in elevated levels of inorganic forms of nitrogen, because the elevated amount of nitrogen might be in the form of proteins, which would indicate better tissue quality (Waskom et al., 2000).

Nitrogen effects on quality

Nitrogen fertilization not only affects the quantity of the harvested material, but also the quality of it. As mentioned earlier, this can either increase or decrease the efficiency of conversion depending on which method is used. Many studies have looked at changes in quality components like non-structural carbohydrates, neutral detergent fiber, acid detergent fiber, acid detergent lignin, and so on. There are very few that have looked at these components in relationship to tissue nitrogen. Most looked for a relationship with applied nitrogen. Since applied nitrogen and tissue nitrogen have a strong correlation, we expected similar results as those found in studies where applied nitrogen was the independent variable. Based on a study by Almodares et al. (2009), we expected sucrose content to decrease with the increase in tissue nitrogen. In their article, they showed results in support of this theory concerning the soluble carbohydrates. They used four nitrogen rates ranging from 50 to 200 kg urea ha^{-1} on corn and sweet sorghum and found that concentration of soluble carbohydrates was lowest at 200 kg urea ha^{-1} for both species. The reason for such results could be that when nitrogen levels are limiting, photosynthesis is not fully used in the synthesis of organic nitrogen compounds and thus sugars are accumulated according to Mengel and Kirby (1978).

Based on a few studies, we expected an increase in ash in relationship with increased tissue nitrogen concentration since ash concentrations increased inwheat and corn (Marino et al.,2009; Li et al., 2010) with nitrogen application. Although ash concentration was found to decrease in wheat in another study (Zebarth et al., 1992). A decrease was also reported in giant reed (Nassi et al., 2008), which shows that there is no universal correlation between tissue nitrogen and ash for all species. The relationship between lignin and nitrogen fertilization or tissue nitrogen concentration also shows some variability among species. For example in poplar, lignin content decreased (Pitre et al 2007) with higher rates of nitrogen. On the other hand, several studies found that the concentration of lignin in maize stover increased with nitrogen fertilization (Morgan, 2011; Li, 2010; Keady, 2000). Similarly lignin concentration also increased in wheat straw (De Giorgio et al., 2008) and kenaf (Adamson et al., 1979). Since sorghum is also a monocot with a similar growth habit to corn and wheat, we expected that sorghum would show a similar response to nitrogen as those crops did.

MATERIALS AND METHODS

Field trials for this project were conducted in the three years from 2008 to 2010 at the Texas A&M Field Laboratory in Burleson County Texas on the Brazos Bottom near College Station (referred to as College Station), and there was an additional location near the town of China, Texas in 2010. The soil at the College Station location is a fluventic ustochrept, and the soil texture is a silty clay loam. . Near China the soil was a League clay. Precipitation for the two locations and the harvest years is shown in Table 1. Each year in every location 3.05 by 7.62m plots were used as the smallest unit to receive a treatment combination of a certain nitrogen rate and a certain variety. Each plot had four rows 76.2 cm apart. The target population for the plots was 175000 plants ha^{-1}. Each year the plots for the nitrogen trials were rotated to an area that was kept fallow in the previous year. Nitrogen rate-variety combinations were assigned to the plots in a randomized complete block design with four repetitions and every year the tests were irrigated by furrow irrigation soon after planting, except for the trials in 2010 near China which were rainfed. Besides the nitrogen treatment, every plot in China received 112 kg P_2O_5 ha^{-1} and 112 kg K_2O ha^{-1} . Potassium and phosphorous were not added in the Brazos Bottom because preliminary soil testing has confirmed that both elements were in abundance. Two harvests were made each year, except for 2008, and in 2010, the second crop failed in China because the soil was constantly water logged due to heavy and frequent rainfalls during the anticipated harvest time.. The second growth received the same amount of fertilizer as the first except in 2010 when it received only 2/3rd rates. The reason for this was the observation that the biomass of the second cuts tend to have much higher tissue nitrogen concentrations than the first cuts, even though the nitrogen effect does not show itself in the yields as much. This can probably be explained by the fact that the second growth already starts out with an established root system which enables it to accumulate more nutrients right from the start, but the yields stay low because the growth period is shorter and has less favorable weather conditions. There were six varieties used each year, three of which were photoperiodic sensitive and did not go into reproductive growth, and the other three were headed varieties of forage sorghum. Five nitrogen rates were used in 2008 and 2009. In 2010, we had two types of field trials: one with five nitrogen rates, which was a multi-cut trial and another with eight rates which was harvested only once. The nitrogen was hand applied to the surface of each row in each plot in the form of ammonium nitrate, except at the China location in 2010 where nitrogen was applied by machine a couple inches below the surface. Where fertilizer was hand applied, it was cultivated below the surface afterwards and in the case of irrigated studies, the plots were irrigated after cultivation.

Soil sampling data from these trials is not available. To counteract this flaw, the nitrogen uptake of the above ground biomass is also given as a reference to yield response and tissue nitrogen concentration (Table 4). A summary of treatments and varieties used in all the trials is presented in Table 2 and trial parameters such as planting and harvest dates, irrigation and seeding are shown in Table 3.

Table 1. Annual precipitation by harvest years and locations

	Annual precipitation by location (cm)	
Year	College Station	China
2008	67	N/A
2009	80	N/A
2010	70	134

Table 2. A display of the various rates of nitrogen and varieties used in the different years, cuts and locations of field trials

Year	Location	Rates kg N/ha	Varieties	# of Cuts
2008	College Station	0,34,78,123,168	Della, Rio, M81E, Silmaker 6500, Sugargraze Ultra, Millennium BMR	1
2009	College Station	0,42,84,126,168	Della, Rio, M18E, Silmaker 6500, Sugargraze Ultra, Millennium BMR	2
2010	College Station, China TX	0,,78,123,168, 224(only in College Station Sugargraze Ultra)	Millennium BMR, Sugargraze Ultra, experimental variety	2
2010	College Station, China TX	0, 39, 78, 118, 157, 196, 235, 274	M81E, Rio, Silmaker 6500	1

Table 3.Planting and harvest dates, method of irrigation and target populations by harvest

Harvest	Planting date	Harvest date	Irrigation	Target population (plants ha-1)
2008	4/17/2008	7/28/2008	gravity	175000
2009 first cut	4/10/2009	7/22/2009	gravity	175000
2009 second cut	-	12/7/2009	gravity	175000
2010 College Station multicut first cut	5/30/2010	8/10/2010	gravity	175000
2010 College Station multicut second cut	-	11/22/2010	gravity	175000
2010 College Station single cut	4/15/2010	10/25/2010	gravity	175000
2010 China multicut first cut	4/21/2010	8/24/2010	None	175000
2010 China single cut	4/21/2010	10/28/2010	None	175000

Table 4. Nitrogen uptake calculated using tissue nitrogen concentration and yield

	Mean N-uptake (N kg ha^{-1}) Harvest							
N-rate (kg N ha^{-1})	2008	2009 first cut	2009 second cut	2010 College Station multicut first cut	2010 College Station multicut second cut	2010 College Station single cut	2010 China multicut first cut	2010 China single cut
0	106.74	62.1	28.73	140.29	58.41	95.91	76.87	86.54
22	-	-	-	-	62	-	-	-
34	128.02	-	-	127.92	-	-	87.56	-
39	-	-	-	-	-	119.57	-	86.9
42	-	87.07	33.19	-	-	-	-	-
52	-	-	-	-	52.89	-	-	-
78	133.74	-	-	146.32	-	125.04	109.17	99.15
82	-	-	-	-	54.3	-	-	-
84	-	102.42	41.75	-	-	-	-	-
112	-	-	-	-	66.98	-	-	-
118	-	-	-	-	-	102.12	-	93.6
123	134.09	-	-	151.2	-	-	118.39	-
126	-	112.73	42.13	-	-	-	-	-
157	-	-	-	-	-	162.65	-	87.06
168	136.58	116.76	46.09	156.5	-	-	153.71	-
196	-	-	-	-	-	121.66	-	118.83
235	-	-	-	-	-	108.27	-	95.78
275	-	-	-	-	-	180.41	-	129.44

Data collection

Total biomass yield of each plot was measured by hand harvesting one row of each plot and using a hanging scale to weigh it. The harvested row was always one of the two middle rows. The harvest length varied but was recorded and accounted for. Care was taken to avoid harvesting from the ends of the rows. In order to measure moisture content and to collect tissue samples, a few of the stalks from the plot were chipped and collected in a sample bag. This sample was also weighed in the field with a digital scale. Later, the sample was dried in an oven at 60°C for 48 hours, then weighed and then dried for another 24 hours to test whether there was any weight change. If there was weight change the sample was placed back for another 24 hours and weighed again. This procedure continued until weight change diminished to nil. The initial wetweight of the sample and the final dry weight were used to calculate moisture content. The dried plant tissue samples were then ground using a Wiley-mill fitted with a 2 mm sieve, and a part of each sample was sent to the Soil, Water, and Forage Testing Laboratory at Texas A&M to determine total nitrogen content using the high temperature dry combustion method (Sweeney and Rose 1989). Another part of this dry and ground sample was used to estimate ash, sucrose, starch, lignin, xylans and cellulose content by near infrared spectrometry using the XDS Near Infrared Rapid Content Analyser manufactured by Foss Analytical. The near infrared spectroscopy method allows for a good estimation of different chemical components by detecting the resonance of the energy reflected from a sample. The reflected spectrum provided with 2 nm accuracy (XDS Lab User Manual 1025846/Rev. 2.0). A calibration curve was used to estimate chemical composition of the samples. The calibration curve was developed for dry sorghum tissue samples by Texas A&M in Cooperation with NREL.

Statistical analyses

All observed components were tested by analysis of variance for nitrogen rate, variety and repetition effect using the proc glm function of SAS 9.2, where both nitrogen rate and repetition were set as classification variables. Means were compared for treatment levels using Fisher's least significant difference at the 0.05 probability level. Scatterplots were created using simple linear regression between observed components and tissue nitrogen concentration and nitrogen rates. In the latter case, means of the dependent variable were displayed at each nitrogen level and nitrogen rate was treated as a continuous variable. Slopes were tested for significance. The data from each harvest was analyzed independently.

RESULTS

Introduction

When analyzing whether applied nitrogen rates had an effect on yield and quality components, we were focused mainly on presenting results about sorghum biomass. Therefore, we tested for variety interactions with applied nitrogen on the various dependent variables. While the variety effect in itself was significant as an intercept shifter for most dependent variables in most harvests(Table 5), results showed that in the majority of harvests there was no variety interaction for the quality components and only half of the harvests had variety interactions for yield (Table 6). Tissue nitrogen, xylan and cellulose had no variety interactions at all. From here on, our results will be presented without concern for variety effect. The analysis of variance for all harvests and all dependent variables can be viewed in Appendix A: Tables A1 through A8.

Table 5. Level of significance of the variety effect affecting yield and quality components of biomass and sweet sorghums at eight harvest dates and two experimental locations

	Dependent variables							
Harvest	Yield	Tissue nitrogen	Ash	Sucrose	Xylan	Cellulose	Lignin	Starch
2008 College Station	*	**	**	**	**	**	**	**
2009 College Station first cut	**	ns	**	**	**	**	**	**
2009 College Station second cut	**	**	**	**	**	**	**	**
2010 College Station multicut first cut	**	ns	**	**	**	**	**	**
2010 College Station multi-cut second cut	ns	**	**	**	**	**	**	**
2010 College Station single-cut	**	**	**	**	**	**	**	**
2010 China multicut first cut	**	*	**	**	**	**	**	**
2010 China single cut	**	**	**	**	**	**	**	**

Table 6. Level of significance of interaction between the variety and N fertilizer effect affecting yield and quality components of biomass and sweet sorghums at eight harvest dates and two experimental locations

	Dependent variables							
Harvest	**Yield**	**Tissue nitrogen**	**Ash**	**Sucrose**	**Xylan**	**Cellulose**	**Lignin**	**Starch**
2008 College Station	ns	ns	Ns	ns	ns	ns	**	**
2009 College Station first cut	ns	ns	Ns	ns	ns	ns	ns	Ns
2009 College Station second cut	ns	ns	**	*	ns	ns	ns	Ns
2010 College Station multicut first cut	*	ns	Ns	*	ns	ns	ns	*
2010 College Station multi-cut second cut	*	ns	Ns	ns	ns	ns	ns	Ns
2010 College Station single-cut	**	ns	Ns	ns	ns	ns	ns	Ns
2010 China multicut first cut	*	ns	Ns	ns	ns	ns	ns	Ns
2010 China single cut	ns	ns	Ns	ns	ns	ns	ns	Ns

More importantly, we have looked at the effect of nitrogen rates on the dependent variables (Table 7). Not surprisingly, we found that nitrogen rate had significant effect on tissue nitrogen in most harvests. The next most affected results were those of ash, sucrose and lignin which were significantly affected by nitrogen application in six out of eight harvests. Yield was not significantly affected in more than half the harvests which suggests other factors were limiting or nitrogen was in excess. Xylan and cellulose were also not affected in the majority of cases.

Nitrogen uptake

Observing how much nitrogen was taken up by the above ground biomass can help with interpreting yield response to applied nitrogen. When nitrogen uptake does not correlate well with applied nitrogen, then it is likely that yield and tissue nitrogen will not have good correlation with applied nitrogen rate either. Therefore nitrogen uptake can be used to interpret yield response. The relationship between nitrogen uptake and applied nitrogen is shown in Table 8. and Figure 1. A significant relationship was found in only 6 harvests. These include the harvests, where yield had any significant relationship with nitrogen rate.

Table 7. Level of significance of N fertilizer effect affecting yield and quality components of biomass and sweet sorghums at eight harvest dates and two experimental locations

	Dependent variables							
Harvest	**Yield**	**Tissue nitrogen**	**Ash**	**Sucrose**	**Xylan**	**Cellulose**	**Lignin**	**Starch**
2008 College Station	ns	*	Ns	*	ns	ns	**	*
2009 College Station first cut	ns	**	**	**	ns	ns	**	**
2009 College Station second cut	**	**	**	ns	*	ns	ns	Ns
2010 College Station multicut first cut	*	ns	*	**	**	**	**	**
2010 College Station multi-cut second cut	ns	**	*	ns	ns	ns	ns	Ns
2010 College Station single-cut	**	**	**	**	*	ns	*	*
2010 China multicut first cut	**	**	**	**	ns	ns	**	Ns
2010 China single cut	ns	**	Ns	**	ns	ns	**	Ns

Table 8. Regression of nitrogen uptake of the above ground sorghum biomass against applied nitrogen rate by harvest

Harvest	Equation	r^2	p-value
2008 College Station	N-uptake (kg N ha^{-1}) = 115.8055 + 0.149049 * N-rate (kg N ha^{-1})	0.679	0.086
2009 College Station total	N-uptake (kg N ha^{-1}) = 98.865 + 0.213 * N-rate (kg N ha^{-1})	0.247	<.0001
2009 College Station first cut	N-uptake (kg N ha^{-1}) = 69.22 + 0.321137 * N-rate (kg N ha^{-1})	0.920	0.010
2009 College Station second cut	N-uptake (kg N ha^{-1}) = 29.646 + 0.103873 * N-rate (kg N ha^{-1})	0.930	0.008
2010 College Station multicut total	N-uptake (kg N ha^{-1}) = 185.75 + 0.128 * N-rate (kg N ha^{-1})	0.052	0.08
2010 College Station multicut first cut	N-uptake (kg N ha^{-1}) = 124.5329 + 0.298087 * N-rate (kg N ha^{-1})	0.731	0.030
2010 College Station multi-cut second cut	N-uptake (kg N ha^{-1}) = 57.06359 + 0.034431 * N-rate (kg N ha^{-1})	0.072	0.662
2010 College Station single-cut	N-uptake (kg N ha^{-1}) = 102.5625 + 0.177644 * N-rate (kg N ha^{-1})	0.332	0.135
2010 China multicut first cut	N-uptake (kg N ha^{-1}) = 74.04646 + 0.434857 * N-rate (kg N ha^{-1})	0.961	0.003
2010 China single cut	N-uptake (kg N ha^{-1}) = 83.1125 + 0.120535 * N-rate (kg N ha^{-1})	0.522	0.043

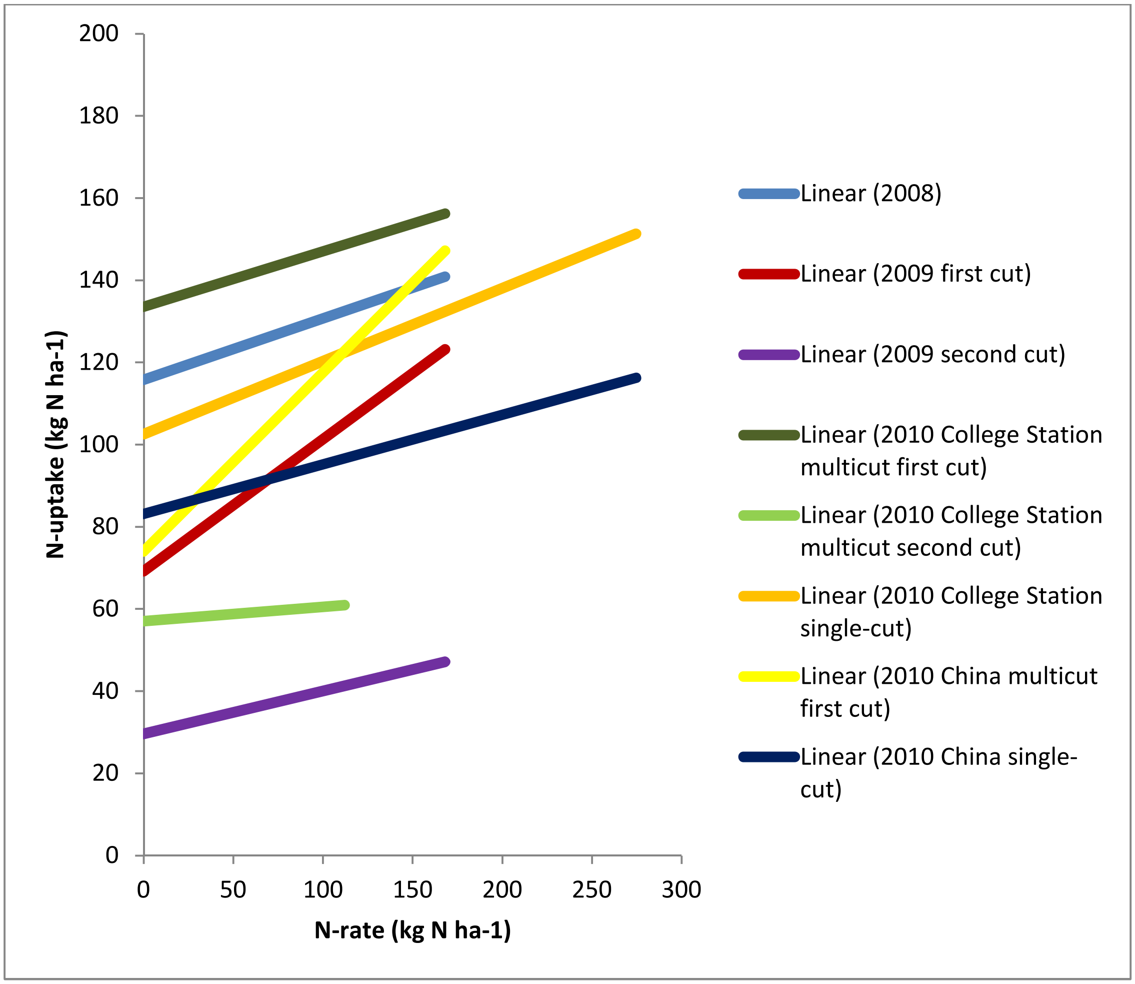

Figure 1. Linear regression of the nitrogen uptake of the above ground biomass against applied nitrogen by harvest

Yield response

The analysis of variance tells us whether yield was affected by the treatments at all, which in this case is the nitrogen rates. It does not tell whether there was any correlation with the levels of the treatment. In this analysis, the dependent variable was dry yield, and the treatment effect was the rate of nitrogen fertilizer applied. It was found that yields were significantly different from each other in 4 out of 8 harvests at the 0.05 level and in 6 out of 8 harvests at the 0.1 level (Appendix A: Tables A1 through A8). In the 2008 College Station harvest and the harvest of the single-cut study near China, in 2010, nitrogen treatment did not have a significant effect at a level of 0.01. In three harvests there was a significant positive linear yield response for nitrogen treatment and in the first cut of 2009 there was a significant quadratic response. Half of all the harvests did not show any significant linear or quadratic response (Table 9). Regression curves are demonstrated in Figures 2 and 3. The coefficients of determination are low when looking at the whole data since the data corresponding to each level of treatment has a large standard deviation. In 2010, only the 1^{st} cut of the multicut trials had a significant yield response. In most cases in both cuts, plots not receiving any nitrogen fertilizer had the lowest average yield, therefore we can say that there was a nitrogen response even in the tests where a linear or quadratic relationship was not found to be significantly fitted by the analysis of variance. A significant quadratic relationship was found in the first cut of 2009 only. In 2008 a quadratic curve also seemed to best describe the relationship between nitrogen treatment and yield even though this was shown not to be significant. In 2008 when there was only one harvest, the unfertilized plots had the lowest yield and maximum yield was reached at 33.6 kg N ha^{-1}. The yields of the second harvest varied more in nitrogen response. In 2008, there was no significant difference in dry yield between the levels of fertilizer at a significance level of 0.05. In 2009, the unfertilized plots also had the lowest yield in the second harvest. Theoretically yield response curves should either hit a plateau or decline after reaching a maximum. The fact that in our trials most of the test showed a linear response suggests that in those years maximum yield could have been reached by using higher nitrogen rates. This is also supported by the fact that in 2009 when we did reach maximum yield at 84 kg N/ha, the crops suffered from fusarium stalk rot which could have been a limiting factor to a good nitrogen response. The highest average yield was reached in 2010 in the first harvest of the multicut trial in Brazos county with 21.6 dry Mg ha^{-1} at 224 kg N ha^{-1}, which was the highest rate used in that trial. There was a significant linear yield increase here from 15.9 dry Mg ha-1 at 0 kg N ha^{-1}. Subsequently, the second cut of this trial didn't show a response to nitrogen fertilization, where the lowest yield was not measured at 0 but at 82 kg N ha^{-1}. The second harvest of this trial had to be harvested early due to an early frost, and it seems nitrogen was not the limiting factor in reaching full yield potential there. The yields of the second harvest in both 2009 and 2010 were lower than the first harvests.

To explain the weak yield response we examined the relationship between yield and the amount of nitrogen taken up by the crops (Table 12, Figure 4). It was found that nitrogen uptake correlates strongly with yield with very low p-values. The correlation coefficient is higher than 0.5 in 6 out of 8 harvests and in the remaining two the correlation coefficient of nitrogen uptake is higher with tissue nitrogen concentration suggesting that in those cases part of the nitrogen taken up by the plants went to increasing nitrogen concentration rather than to supporting growth. Applied nitrogen only had a significant relationship with yield in 4 harvests. It turns out that N uptake also had significant relationship with N-rate in those 4 cases. Harvests with bad yield responses also didn't have a connection between applied nitrogen and nitrogen uptake. In those cases it's possible that the soil already had high amounts of nitrogen.

We also examined the relationship between tissue nitrogen and yield (Table 11). Based on reports from an earlier version of this field trial which were conducted in 2006 and 2007 in a similar fashion (Blumenthal, 2008), we expected a quadratic relationship. In Dr. Jürg Blumenthal's study the tissue nitrogen increased with yield up to a certain point and then decreased again with further increases in yield. Unfortunately in the harvest years of this project we did not get such a relationship. No significant quadratic relationship was found and even where a linear relationship was found to be significant, the correlation coefficients were extremely low, the highest one being 0.067. Therefore no conclusions can be drawn from this data about the relationship between yield and tissue nitrogen.

Table 9. Regression of above ground sorghum biomass yield against applied nitrogen rates by year and location

Harvest	Equation	r^2	p-value
2008 College Station	Yield (Mg ha^{-1})=16.841 + 0.005*applied nitrogen (kg N ha^{-1}) - 0.0002*applied nitrogen (kg N ha^{-1})^2	0.027	0.201
2009 College Station total	Yield (Mg ha^{-1}) = 13.939 + 0.006 * applied nitrogen (kg N ha^{-1})	0.029	0.063
2009 College Station first cut	Yield (Mg ha^{-1}) = 11.071 + 0.003*applied nitrogen (kg N ha^{-1}) - 0.0002*applied nitrogen (kg N ha^{-1})^2	0.056	0.034
2009 College Station second cut	Yield (Mg ha^{-1}) = 3.582 + 0.009*applied nitrogen (kg N ha^{-1})	0.046	0.019
2010 College Station multicut total	Yield (Mg ha^{-1}) = 20.664 + 0.009 * applied nitrogen (kg N ha^{-1})	0.026	0.219
2010 College Station multicut first cut	Yield (Mg ha^{-1}) = 15.231 + 0.020*applied nitrogen (kg N ha^{-1})	0.110	0.008
2010 College Station multi-cut second cut	Yield (Mg ha^{-1}) = 5.518 - 0.008*applied nitrogen (kg N ha^{-1})	0.039	0.132
2010 College Station single-cut	Yield (Mg ha^{-1}) = 14.662 + 0.006*applied nitrogen (kg N ha^{-1})	0.009	0.362
2010 China multicut first cut	Yield (Mg ha^{-1}) = 10.592 + 0.028*applied nitrogen (kg N ha^{-1})	0.155	0.002
2010 China single cut	Yield (Mg ha^{-1}) = 13.645 - 0.003*applied nitrogen (kg N ha^{-1})	0.002	0.642

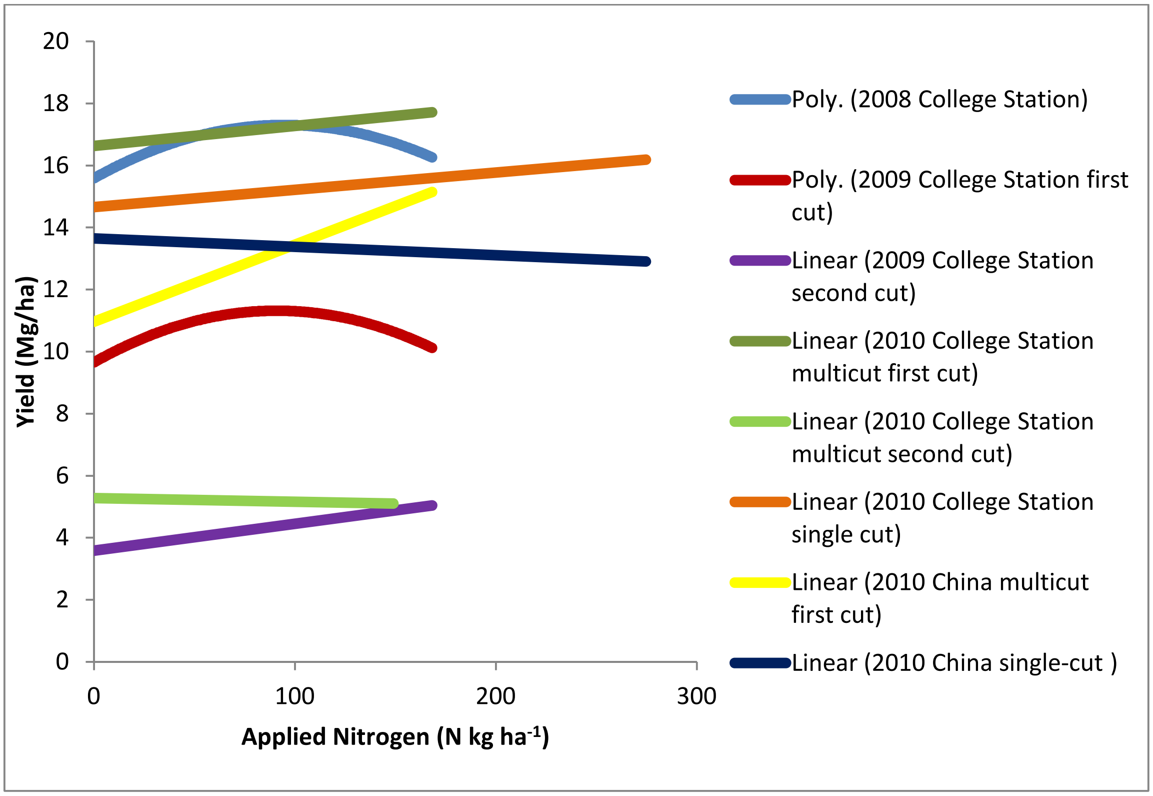

Figure 2. Regression of above ground sorghum biomass yield against applied nitrogen rates across years and locations

Table 10. Regression of mean above ground sorghum biomass yield against applied nitrogen rates by year and location

Harvest	Equation	r^2	p-value
2008 College Station	Yield (Mg ha^{-1}) = 16.841 + 0.005*applied nitrogen (kg N ha^{-1}) - 0.0002*applied nitrogen (kg N ha^{-1})^2	0.725	0.275
2009 College Station total	Yield (Mg ha^{-1}) = 12.697 + 0.035 * applied nitrogen (kg N ha^{-1}) – 0.0001 * applied nitrogen (kg N ha^{-1})^2	0.979	0.021
2009 College Station first cut	Yield (Mg ha^{-1}) = 11.076 + 0.003*applied nitrogen (kg N ha^{-1}) - 0.0002*applied nitrogen (kg N ha^{-1})^2	0.987	0.013
2009 College Station second cut	Yield (Mg ha^{-1}) = 3.582 + 0.009*applied nitrogen (kg N ha^{-1})	0.508	0.176
2010 College Station multicut first cut	Yield (Mg ha^{-1}) = 15.001 + 0.024*applied nitrogen (kg N ha^{-1})	0.871	0.007
2010 College Station multi-cut second cut	Yield (Mg ha^{-1}) = 5.518 - 0.008*applied nitrogen (kg N ha^{-1})	0.32	0.325
2010 College Station single-cut	Yield (Mg ha^{-1}) = 14.662 + 0.006*applied nitrogen (kg N ha^{-1})	0.045	0.614
2010 China multicut first cut	Yield (Mg ha^{-1}) = 11.068 + 0.024*applied nitrogen (kg N ha^{-1})	0.846	0.027
2010 China single cut	Yield (Mg ha^{-1}) = 13.645 - 0.003*applied nitrogen (kg N ha^{-1})	0.049	0.598

Table 11. Regression of above ground sorghum biomass yield against tissue nitrogen concentration by year and location

Harvest	Equation	r^2	p-value
2008 College Station	Yield (Mg ha^{-1}) = 19.254 - 0.344*tissue nitrogen (g kg^{-1})	0.032	0.049
2009 College Station first cut	Yield (Mg ha^{-1})= 10.276 + 0.035*tissue nitrogen (g kg^{-1})	0.001	0.678
2009 College Station second cut	Yield (Mg ha^{-1})= 7.791 - 0.383*tissue nitrogen (g kg^{-1})	0.054	0.011
2010 College Station multicut first cut	Yield (Mg ha^{-1}) = 18.465 - 0.163*tissue nitrogen (g kg^{-1})	0.004	0.607
2010 College Station multi-cut second cut	Yield (Mg ha^{-1}) = 6.804 - 0.128*tissue nitrogen (g kg^{-1}) - 0.057*tissue nitrogen (g kg^{-1})^2	0.071	0.122
2010 College Station single-cut	Yield (Mg ha^{-1}) = 10.989 + 0.546*tissue nitrogen (g kg^{-1})	0.031	0.085
2010 China multicut first cut	Yield (Mg ha^{-1}) = 8.217 + 0.555*tissue nitrogen (g kg^{-1})	0.067	0.046
2010 China single cut	Yield (Mg ha^{-1}) = 18.831 - 0.727*tissue nitrogen (g kg^{-1})	0.051	0.027

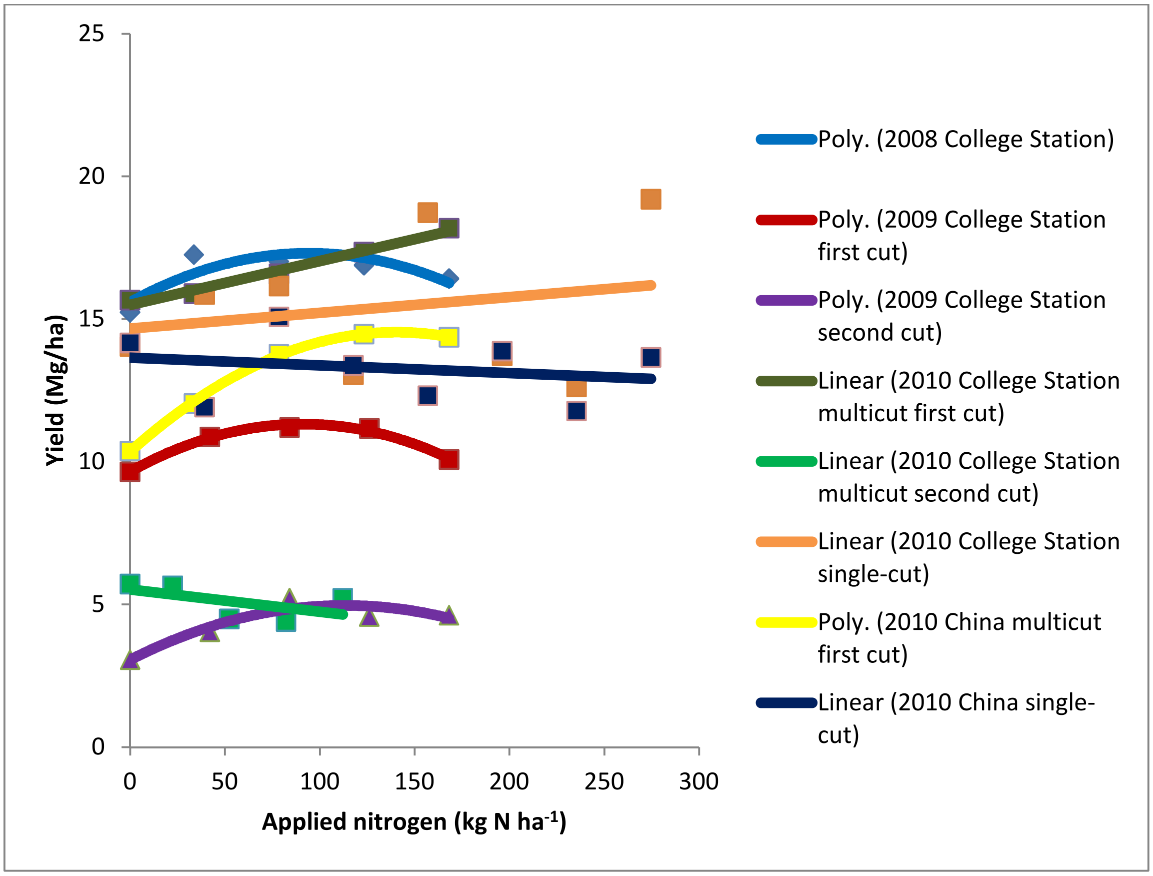

Figure 3. Regression of above ground sorghum biomass yield averaged over nitrogen rates against nitrogen rate by harvest

Table 12. Regression of above ground sorghum biomass yield against nitrogen uptake by harvest

Harvest	Equation	r^2	p-value
2008 College Station	Yield (Mg ha^{-1}) = 9.33291 + 0.05661*nitrogen uptake (kg N ha^{-1})	0.3572	<.0001
2009 College Station first cut	Yield (Mg ha^{-1}) = 6.78848 + 0.03956*nitrogen uptake (kg N ha^{-1})	0.3593	<.0001
2009 College Station second cut	Yield (Mg ha^{-1}) = 0.2303 + 0.10634*nitrogen uptake (kg N ha^{-1})	0.8495	<.0001
2010 College Station multicut first cut	Yield (Mg ha^{-1}) = 7.08039 + 0.06701*nitrogen uptake (kg N ha^{-1})	0.5395	<.0001
2010 College Station multi-cut second cut	Yield (Mg ha^{-1}) = 1.08543 + 0.06888*nitrogen uptake (kg N ha^{-1})	0.7268	<.0001
2010 College Station single-cut	Yield (Mg ha^{-1}) = 4.94838 + 0.08252*nitrogen uptake (kg N ha^{-1})	0.7538	<.0001
2010 China multicut first cut	Yield (Mg ha^{-1}) = 5.37743 + 0.06835*nitrogen uptake (kg N ha^{-1})	0.6823	<.0001
2010 China single cut	Yield (Mg ha^{-1}) = 2.72872 + 0.10682*nitrogen uptake (kg N ha^{-1})	0.6319	<.0001

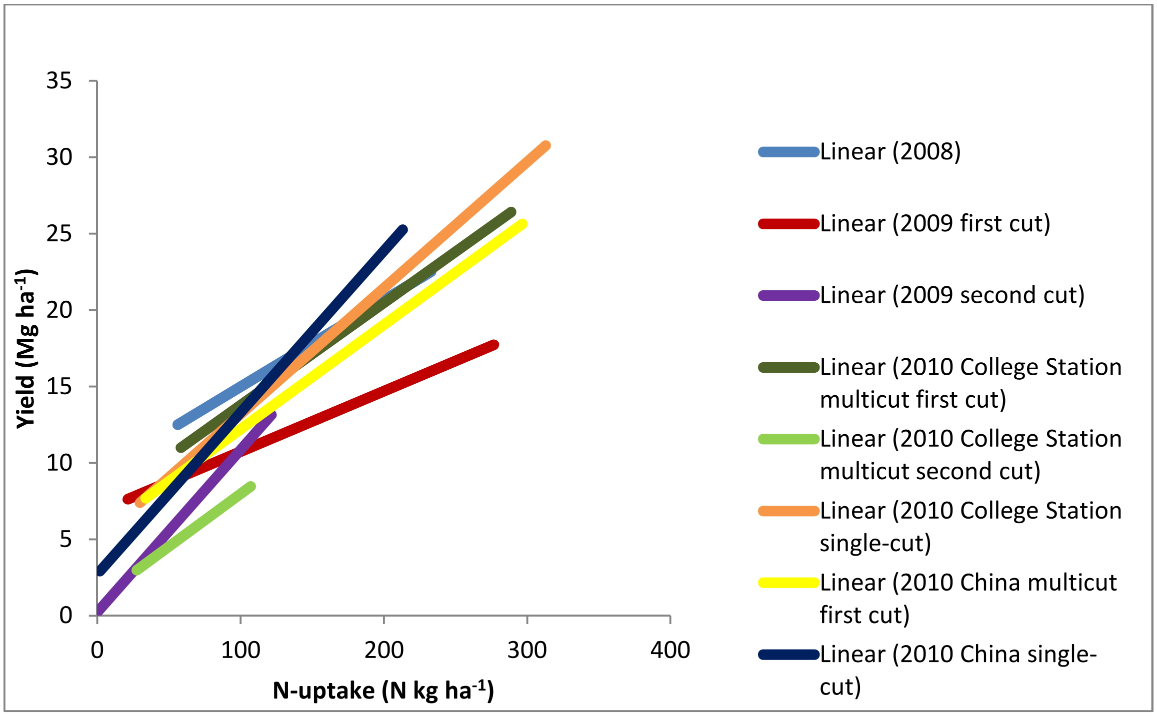

Figure 4. Regression of above ground sorghum biomass yield against nitrogen uptake by harvest

Tissue nitrogen

Measuring the tissue nitrogen concentration of the harvested samples and the yield, is necessary to calculate how much nitrogen is removed by the crop. It can also be determined whether concentration is affected by the different levels of nitrogen fertilization. The analysis of variance of the data showed that there was a treatment effect on tissue nitrogen in all but the first harvest of the 2010 College Station multicut test. (Appendix A: Tables A1 through A8). In that test alone the means were not significantly different. Observations showed that between nitrogen rates and mean tissue nitrogen concentrations for each rate, a linear regression could be applied. In most cases this relationship was highly significant and in all 8 harvests the highest nitrogen rate corresponded with the highest tissue nitrogen concentrations. The lowest tissue nitrogen concentrations were only paired up by no nitrogen treatment in only 3 cases (Figures 5 and 6). This was probably caused by residual nitrogen in the soil. Nevertheless a linear relationship between applied nitrogen and tissue nitrogen concentration was found to be significant in 7 harvests (Table 13). Interestingly the second cut of the College Station multicut study had an r^2 of 0.953 when looking at mean tissue nitrogen concentrations (Table 14) and had a significant relationship even though the first cut failed even the analysis of variance regarding tissue nitrogen concentration. The linear relationships are always positive with varying steepness of slope. The range of tissue nitrogen concentrations between 0 kg N ha^{-1} to the highest level of nitrogen application was about 5g kg^{-1} in the first cut of the 2009 study, when looking at means, which was the widest range of all the studies. In 2009, there were only 5 levels including no application, whereas in the 2010 single cut studies there were 8 levels of application but the ranges were only about 3 g kg^{-1} for both locations. Noticeably, the first harvest of 2009 also showed a very strong quadratic nitrogen yield response which indicated that after reaching maximum yield the crops consumed luxurious amounts of nitrogen. In this study, only the total amount of tissue nitrogen was tested for, therefore we do not know what portion of the tissue nitrogen concentration was in proteins and what portion was in the form of nitrates.

Overall the increase in tissue nitrogen was very noticeable. The biggest relative difference in the lowest average and the highest treatment average was in the first cut of 2009 where the tissue nitrogen concentration of the highest level of treatment was about 180% of the tissue nitrogen concentration average of the untreated plots. This shows that the effect of nitrogen fertilization on tissue nitrogen concentration is not negligible. Similarly to yield, tissue nitrogen concentration correlated well to nitrogen uptake. Although the correlation coefficients were generally higher with yield, except in two cases where the r^2s with yield were lower than 0.5 but were higher with tissue nitrogen.

Table 13. Regression of tissue nitrogen concentration of the above ground sorghum biomass against applied nitrogen rates by harvest

Harvest	Equation	r^2	p-value
2008 College Station	tissue nitrogen (g kg^{-1}) = 7.216 + 0.007*applied nitrogen (kg N ha^{-1})	0.050	0.014
2009 College Station first cut	tissue nitrogen (g kg^{-1}) = 6.602 + 0.029*applied nitrogen (kg N ha^{-1})	0.369	<.0001
2009 College Station second cut	tissue nitrogen (g kg^{-1}) = 8.557 + 0.006*applied nitrogen (kg N ha^{-1})	0.067	0.004
2010 College Station multicut first cut	tissue nitrogen (g kg^{-1}) = 8.466 + 0.003*applied nitrogen (kg N ha^{-1})	0.017	0.310
2010 College Station multi-cut second cut	tissue nitrogen (g kg^{-1}) = 10.202 + 0.026*applied nitrogen (kg N ha^{-1})	0.285	<.0001
2010 College Station single-cut	tissue nitrogen (g kg^{-1}) = 6.906 + 0.009*applied nitrogen (kg N ha^{-1})	0.215	<.0001
2010 China multicut first cut	tissue nitrogen (g kg^{-1}) = 7.074 + 0.016*applied nitrogen (kg N ha^{-1})	0.224	0.0001
2010 China single cut	tissue nitrogen (g kg^{-1}) = 6.348 + 0.009*applied nitrogen (kg N ha^{-1})	0.293	<.0001

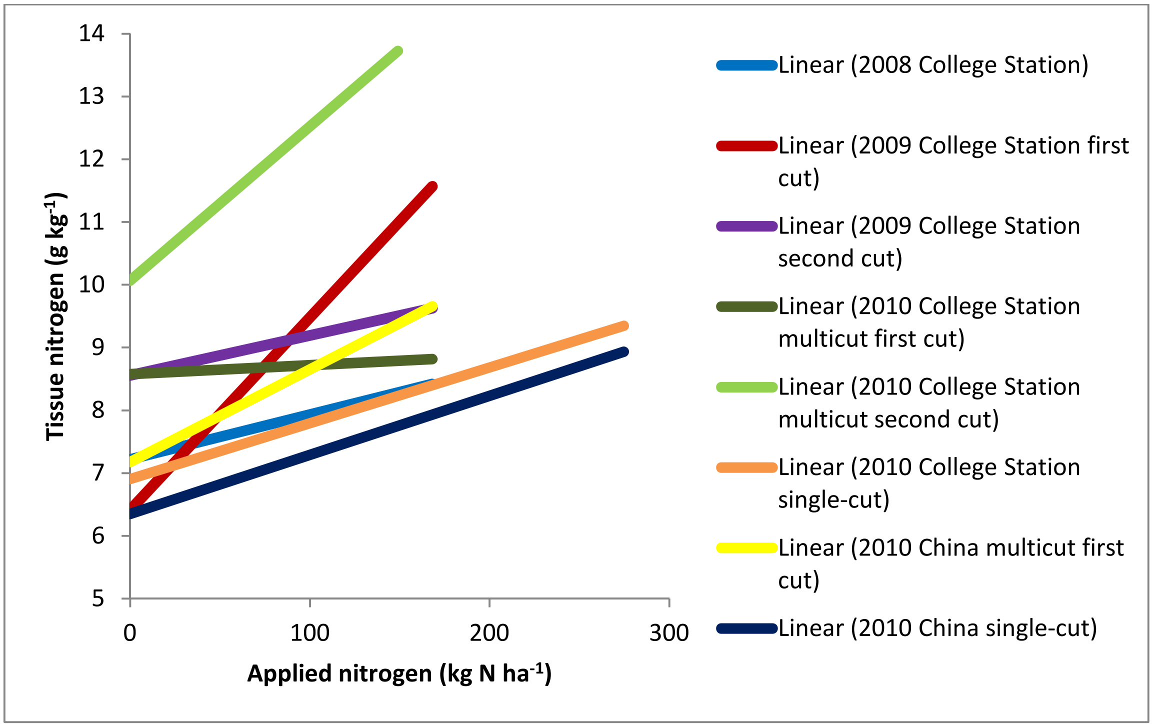

Figure 5. Regression of tissue nitrogen concentration of the above ground sorghum biomass against applied nitrogen rate by year and location

Table 14. Regression of mean tissue nitrogen concentration of the above ground sorghum biomass against applied nitrogen rates by harvest

Harvest	Equation	r^2	p-value
2008 College Station	tissue nitrogen (g kg^{-1}) = 7.217 + 0.007*applied nitrogen (kg N ha^{-1})	0.933	0.008
2009 College Station first cut	tissue nitrogen (g kg^{-1}) = 6.574 + 0.029*applied nitrogen (kg N ha^{-1})	0.996	<.0001
2009 College Station second cut	tissue nitrogen (g kg^{-1}) = 8.556 + 0.006*applied nitrogen (kg N ha^{-1})	0.310	0.329
2010 College Station multicut first cut	tissue nitrogen (g kg^{-1}) = 8.388 + 0.005*applied nitrogen (kg N ha^{-1})	0.490	0.121
2010 College Station multi-cut second cut	tissue nitrogen (g kg^{-1}) = 10.344 + 0.022*applied nitrogen (kg N ha^{-1})	0.953	0.001
2010 College Station single-cut	tissue nitrogen (g kg^{-1}) = 6.907 + 0.009*applied nitrogen (kg N ha^{-1})	0.932	<.0001
2010 China multicut first cut	tissue nitrogen (g kg^{-1}) = 7.049 + 0.016*applied nitrogen (kg N ha^{-1})	0.684	0.084
2010 China single cut	tissue nitrogen (g kg^{-1}) = 6.35 + 0.009*applied nitrogen (kg N ha^{-1})	0.819	0.002

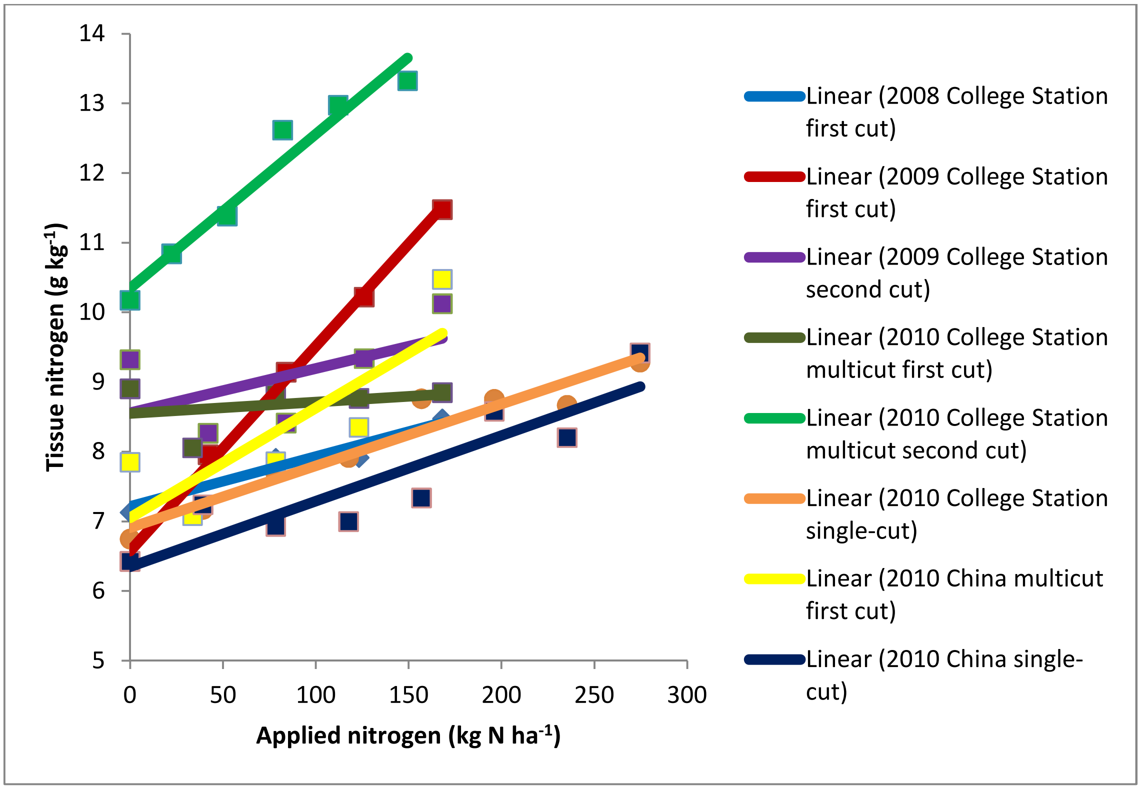

Figure 6. Regression of mean tissue nitrogen concentration of the above ground sorghum biomass against applied nitrogen rate by year and location

Ash

For every test year, harvest and location, ash concentration increased with tissue nitrogen concentration (Table 17, Figure 7) and also with fertilizer nitrogen rate (Table15, 16), although the latter was not always significant. On the other hand, the positive relationship with tissue nitrogen concentration, using the whole data, was found to be significant at the 0.0001 level in every case (Table 17). From lowest to highest levels of nitrogen fertilization, there was a 5 to 28 percent increase in ash concentration of the harvested biomass. The r^2s were between 0.19 and 0.61. The lowest ash concentration was 46.82 g kg^{-1} at 34 kg N ha^{-1} in the first cut of the 2010 College Station multicut trial. The highest ash concentration was 74.31 g kg^{-1} at 149 kg N ha^{-1} in the second harvest of the 2010 College Station multicut trial.

The observation that ash increases with tissue nitrogen concentration and nitrogen rate, might be due to the plant trying to balance nutrients in its system. Therefore it takes up more of the other elements, the bulk of it which is most likely potassium.

Table 15. Regression of ash concentration of the above ground sorghum biomass against applied nitrogen rates by harvest

Harvest	Equation	r^2	p-value
2008 College Station	ash (g kg^{-1}) = 58.530 + 0.014*applied nitrogen (kg N ha^{-1})	0.016	0.172
2009 College Station first cut	ash (g kg^{-1}) = 58.582 + 0.070*applied nitrogen (kg N ha^{-1})	0.242	<.0001
2009 College Station second cut	ash (g kg^{-1}) = 63.898 + 0.021*applied nitrogen (kg N ha^{-1})	0.058	0.008
2010 College Station multicut first cut	ash (g kg^{-1}) = 47.197 + 0.033*applied nitrogen (kg N ha^{-1})	0.045	0.094
2010 College Station multi-cut second cut	ash (g kg^{-1}) = 64.227 + 0.055*applied nitrogen (kg N ha^{-1})	0.104	0.012
2010 College Station single-cut	ash (g kg^{-1}) = 56.523 + 0.023*applied nitrogen (kg N ha^{-1})	0.068	0.010
2010 China multicut first cut	ash (g kg^{-1}) = 52.960 + 0.050*applied nitrogen (kg N ha^{-1})	0.046	0.099
2010 China single cut	ash (g kg^{-1}) = 55.127 + 0.018*applied nitrogen (kg N ha^{-1})	0.071	0.009

Table 16. Regression of mean ash concentration of the above ground sorghum biomass against applied nitrogen rate by harvest

Harvest	Equation	r^2	p-value
2008 College Station	ash (g kg^{-1}) = 58.530 + 0.014*applied nitrogen (kg N ha^{-1})	0.687	0.083
2009 College Station first cut	ash (g kg^{-1}) = 58.51 + 0.071*applied nitrogen (kg N ha^{-1})	0.992	0.000
2009 College Station second cut	ash (g kg^{-1}) = 63.9 + 0.021*applied nitrogen (kg N ha^{-1})	0.614	0.117
2010 College Station multicut first cut	ash (g kg^{-1}) = 46.895 + 0.043*applied nitrogen (kg N ha^{-1})	0.600	0.071
2010 College Station multi-cut second cut	ash (g kg^{-1}) = 63.889 + 0.065*applied nitrogen (kg N ha^{-1})	0.892	0.005
2010 College Station single-cut	ash (g kg^{-1}) = 56.523 + 0.023*applied nitrogen (kg N ha^{-1})	0.886	0.001
2010 China multicut first cut	ash (g kg^{-1}) = 55.063 + 0.033*applied nitrogen (kg N ha^{-1})	0.231	0.412
2010 China single cut	ash (g kg^{-1}) = 55.129 + 0.018*applied nitrogen (kg N ha^{-1})	0.785	0.003

Table 17. Regression of ash concentration of the above ground sorghum biomass against tissue nitrogen concentration by harvest

Harvest	Equation	r^2	p-value
2008 College Station	ash (g kg^{-1}) = 42.007 + 2.265*tissue nitrogen (g kg^{-1})	0.425	<.0001
2009 College Station first cut	ash (g kg^{-1}) = 43.587 + 2.304*tissue nitrogen (g kg^{-1})	0.608	<.0001
2009 College Station second cut	ash (g kg^{-1}) = 48.482 + 1.891*tissue nitrogen (g kg^{-1})	0.284	<.0001
2010 College Station multicut first cut	ash (g kg^{-1}) = 25.610 + 2.810*tissue nitrogen (g kg^{-1})	0.191	<.0001
2010 College Station multi-cut second cut	ash (g kg^{-1}) = 37.996 + 2.519*tissue nitrogen (g kg^{-1})	0.507	<.0001
2010 College Station single-cut	ash (g kg^{-1}) = 30.747 + 3.553*tissue nitrogen (g kg^{-1})	0.621	<.0001
2010 China multicut first cut	ash (g kg^{-1}) = 19.780 + 4.461*tissue nitrogen (g kg^{-1})	0.404	<.0001
2010 China single cut	ash (g kg^{-1}) = 37.055 + 2.692*tissue nitrogen (g kg^{-1})	0.468	<.0001

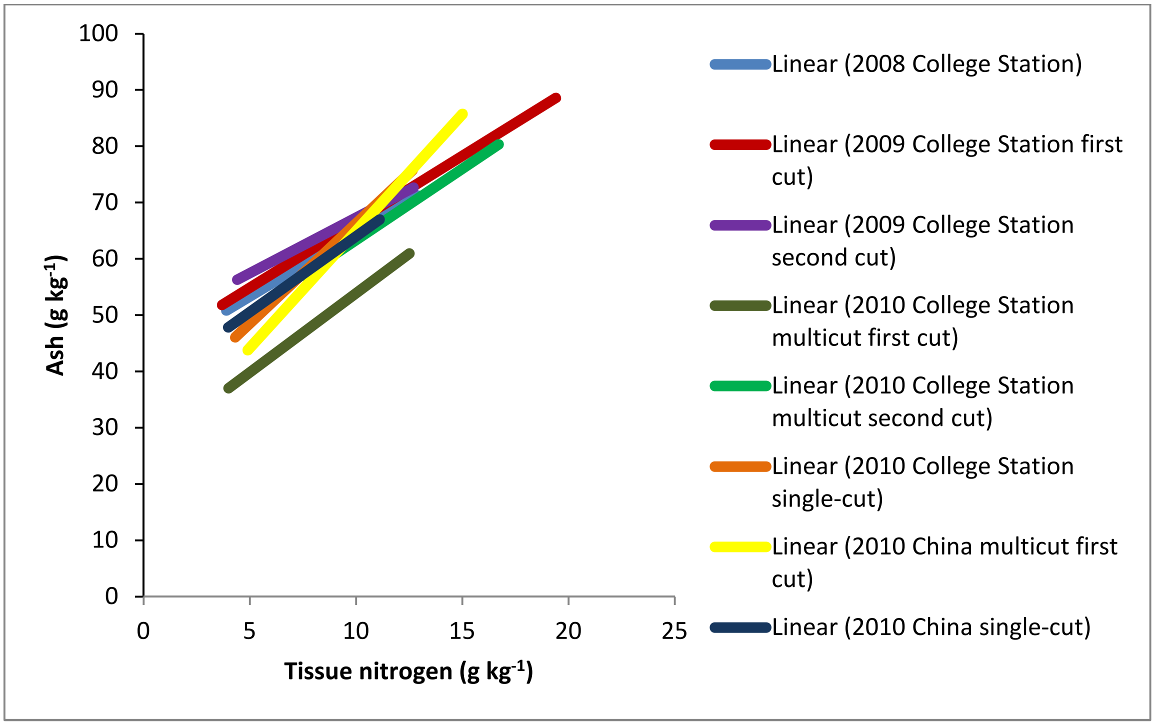

Figure 7. Regression of ash concentration of the above ground sorghum biomass against tissue nitrogen concentration by harvest

Sucrose

Sucrose concentration exhibited a linear negative relationship with tissue nitrogen (Figure 8). In every study, there was a highly significant negative relationship between sucrose and tissue nitrogen concentrations of the harvested biomass. In 6 cases, the p-value was less than 0.0001 (Table 21). The correlation with applied nitrogen rates was not as obvious when looking at all the data points from the individual harvests (Table 18) since there was a wide distribution of sucrose concentrations for each level of nitrogen treatment in all the harvests. Therefore, a negative relationship between applied nitrogen and sucrose was only significant in 5 out of 8 cases at the 0.1 level and only in 3 cases at the 0.05 level. However, when looking at mean sucrose concentrations for nitrogen application levels, the negative linear relationship was found to be significant in 7 out of 8 harvests at the 0.05 level (Table 19). The highest mean concentrations of sucrose were found in the unfertilized treatments. The highest measured average was 146.94 g kg^{-1} at 0 kg N ha^{-1} in the first cut of 2009, and the lowest measured was 70.85 g kg^{-1} at 321 kg N ha^{-1} in the first cut of the 2010 College Station multi-cut trial. This trial, which had 6 nitrogen rates, had the widest range in sucrose concentration, ranging from 118.63 g kg^{-1} at 48 kg N ha^{-1} to 70.85 g kg^{-1} at 321 kg N ha^{-1}. Comparatively, the single cut study in College Station which had 8 fertilizer nitrogen rates had a smaller range between 112.4 and 137.65 g kg^{-1} sucrose. It would be convenient if the two largest ranges came from the two singlecut studies with the widest range in fertilizer treatments, but this was not the case since the second largest range resulted from the first cut of the China multicut study which only had 5 levels of treatment. The lowest range came from the second cut of 2009 which also showed weak yield and tissue nitrogen response to fertilization.

The amount of sucrose produced per hectare was calculated using biomass yield and sucrose concentration of the dried biomass. The total sucrose yielded per hectare did not show a god relationship to nitrogen rate in any of the harvests, although the trend was negative in 7 out of 8 cases (Table 20). The mean amount of sucrose produced by N-rate ranged from 0.477 Mg ha^{-1} to 2.528 Mg ha^{-1}. These measurements are based on near infrared spectroscopy analysis of dry biomass and not on brix measurements of the juice.

Table 18. Regression of sucrose concentration of the above ground sorghum biomass against applied nitrogen rates concentration by harvest

Harvest	Equation	r^2	p-value
2008 College Station	sucrose (g kg^{-1}) = 122.146 - 0.072*applied nitrogen (kg N ha^{-1})	0.029	0.063
2009 College Station first cut	sucrose (g kg^{-1}) = 144.693 - 0.148*applied nitrogen (kg N/ha)	0.107	0.001
2009 College Station second cut	sucrose (g kg^{-1}) = 129.506 - 0.023*applied nitrogen (kg N ha^{-1})	0.005	0.457
2010 College Station multicut first cut	sucrose (g kg^{-1}) = 123.071 - 0.129*applied nitrogen (kg N ha^{-1})	0.053	0.067
2010 College Station multi-cut second cut	sucrose (g kg^{-1}) = 117.445 - 0.080*applied nitrogen (kg N ha^{-1})	0.018	0.310
2010 College Station single-cut	sucrose (g kg^{-1}) = 135.554 - 0.086*applied nitrogen (kg N ha^{-1})	0.056	0.021
2010 China multicut first cut	sucrose (g kg^{-1}) = 103.790 - 0.139*applied nitrogen (kg N ha^{-1})	0.033	0.166
2010 China single cut	sucrose (g kg^{-1}) = 122.500 - 0.098*applied nitrogen (kg N ha^{-1})	0.125	0.001

Table 19. Regression of mean sucrose concentration of the above ground sorghum biomass against applied nitrogen rate by harvest

Harvest	Equation	r^2	p-value
2008 College Station	sucrose (g kg^{-1}) = 122.146 - 0.072*applied nitrogen (kg N ha^{-1})	0.783	0.046
2009 College Station first cut	sucrose (g kg^{-1}) = 144.93 - 0.149*applied nitrogen (kg N ha^{-1})	0.967	0.003
2009 College Station second cut	sucrose (g kg^{-1}) = 129.504 - 0.023*applied nitrogen (kg N ha^{-1})	0.822	0.034
2010 College Station multicut first cut	sucrose (g kg^{-1}) = 124.963 - 0.176*applied nitrogen (kg N ha^{-1})	0.662	0.049
2010 College Station multi-cut second cut	sucrose (g kg^{-1}) = 119.562 - 0.137*applied nitrogen (kg N ha^{-1})	0.669	0.047
2010 College Station single-cut	sucrose (g kg^{-1}) = 135.555 - 0.086*applied nitrogen (kg N ha^{-1})	0.792	0.003
2010 China multicut first cut	sucrose (g kg^{-1}) = 95.671 - 0.074*applied nitrogen (kg N ha^{-1})	0.091	0.621
2010 China single cut	sucrose (g kg^{-1}) = 122.499 - 0.098*applied nitrogen (kg N ha^{-1})	0.875	0.001

Table 20. Regression of the total amount of sucrose produced by the biomass against N-rate by harvest and year

Harvest	Equation	r^2	p-value
2008 College Station	Total sucrose (Mg ha^{-1}) = 2.00049 - 0.00089207 * N-rate (kg N ha^{-1})	0.008	0.340
2009 College Station total	Total sucrose (Mg ha^{-1}) = 1.95 – 0.0001 * N-rate (kg N ha^{-1})	0.0005	0.81
2009 College Station first cut	Total sucrose (Mg ha^{-1}) = 1.48839 - 0.0012 *N-rate(kg N ha^{-1})	0.030	0.060
2009 College Station second cut	Total sucrose (Mg ha^{-1}) = 0.46088 - 0.00098633 * N-rate (kg N ha^{-1})	0.035	0.040
2010 College Station multicut total	Total sucrose (Mg ha^{-1}) = 2.527 – 0.001 * N-rate (kg N ha^{-1})	0.019	0.3
2010 College Station multicut first cut	Total sucrose (Mg ha^{-1}) = 1.86594 - 0.00065548 * N-rate (kg N ha^{-1})	0.007	0.508
2010 College Station multi-cut second cut	Total sucrose (Mg ha^{-1}) = 0.64809 - 0.00117 * N-rate (kg N ha^{-1})	0.056	0.071
2010 College Station single-cut	Total sucrose (Mg ha^{-1}) = 1.95403 - 0.00050413 * N-rate (kg N ha^{-1})	0.003	0.586
2010 China multicut first cut	Total sucrose (Mg ha^{-1}) = 1.03989 + 0.00062201 * N-rate (kg N ha^{-1})	0.005	0.608
2010 China single cut	Total sucrose (Mg ha^{-1}) = 1.7436 - 0.00186 * N-rate (kg N ha^{-1})	0.045	0.037

Table 21. Regression of sucrose concentration of the above ground sorghum biomass against tissue nitrogen concentration by harvest

Harvest	Equation	r^2	p-value
2008 College Station	sucrose (g kg^{-1}) = 167.486 - 6.562*tissue nitrogen (g kg^{-1})	0.250	<.0001
2009 College Station first cut	sucrose (g kg^{-1}) = 182.346 - 5.530*tissue nitrogen (g kg^{-1})	0.347	<.0001
2009 College Station second cut	sucrose (g kg^{-1}) = 176.478 - 5.375*tissue nitrogen (g kg^{-1})	0.161	<.0001
2010 College Station multicut first cut	sucrose (g kg^{-1}) = 161.001 - 5.659*tissue nitrogen (g kg^{-1})	0.062	0.0479
2010 College Station multi-cut second cut	sucrose (g kg^{-1}) = 201.741 - 7.638*tissue nitrogen (g kg^{-1})	0.386	<.0001
2010 College Station single-cut	sucrose (g kg^{-1}) = 257.499 - 16.453*tissue nitrogen (g kg^{-1})	0.751	<.0001
2010 China multicut first cut	sucrose (g kg^{-1}) = 174.261 - 9.803*tissue nitrogen (g kg^{-1})	0.177	0.0008
2010 China single cut	sucrose (g kg^{-1}) = 193.097 - 10.997*tissue nitrogen (g kg^{-1})	0.479	<.0001

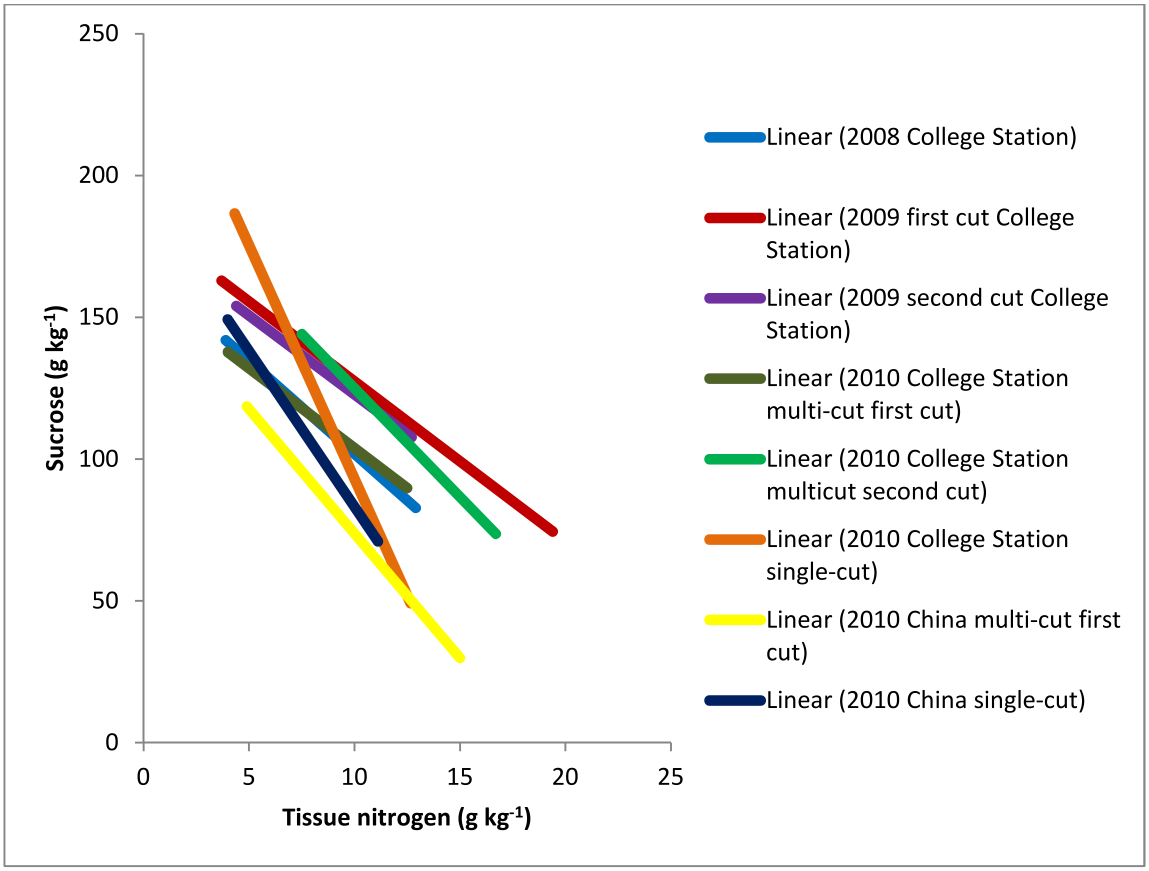

Figure 8. Regression of sucrose concentration of the above ground sorghum biomass against tissue nitrogen concentration by harvest

Starch

The ANOVA results showed that starch concentrations were significantly different from each other in only 4 harvests for the different levels of nitrogen treatment (Table 22). However the overall tendency was for starch content to decrease with higher nitrogen rates and with the increase of tissue nitrogen concentration. Regression with fertilizer nitrogen was significant in 4 harvests for the whole dataset and in 5 harvests for means data at the 0.05 level and in 6 harvests for averaged data at the 0.1 level (Table 22, 23). Relationships with tissue nitrogen were similar to those with fertilizer nitrogen, but the significances here were much stronger (Table 24). The r^2s are low except in the case of the two single cut trials where it was 0.44 in College Station and 0.26 in China. Despite this it can be seen (Figure 9) that the overall trend was for starch to decrease with tissue nitrogen concentration. The trend was positive only in one study in the second cut of 2009 where the r^2 was very low.

Table 22. Regression of starch concentration of the above ground sorghum biomass against applied nitrogen rates by harvest

Harvest	Equation	r^2	p-value
2008 College Station	starch (g kg^{-1}) = 138.619 - 0.105*applied nitrogen (kg N ha^{-1})	0.020	0.121
2009 College Station first cut	starch (g kg^{-1}) = 188.802 - 0.223*applied nitrogen (kg N ha^{-1})	0.042	0.025
2009 College Station second cut	starch (g kg^{-1}) = 149.797 + 0.004*applied nitrogen (kg N ha^{-1})	<.0001	0.951
2010 College Station multicut first cut	starch (g kg^{-1}) = 148.620 - 0.240*applied nitrogen (kg N ha^{-1})	0.116	0.006
2010 College Station multi-cut second cut	starch (g kg^{-1}) = 133.690 - 0.104*applied nitrogen (kg N ha^{-1})	0.012	0.402
2010 College Station single-cut	starch (g kg^{-1}) = 140.376 - 0.088*applied nitrogen (kg N ha^{-1})	0.048	0.039
2010 China multicut first cut	starch (g kg^{-1}) = 111.289 - 0.069*applied nitrogen (kg N ha^{-1})	0.008	0.499
2010 China single cut	starch (g kg^{-1}) = 127.901 - 0.075*applied nitrogen (kg N ha^{-1})	0.047	0.034

Table 23. Regression of mean starch concentration of the above ground sorghum biomass against applied nitrogen rate by harvest

Harvest	Equation	r^2	p-value
2008 College Station	starch (g kg^{-1}) = 138.619 - 0.105*applied nitrogen (kg N ha^{-1})	0.771	0.050
2009 College Station first cut	starch (g kg^{-1}) = 189.950 - 0.236*applied nitrogen (kg N ha^{-1})	0.912	0.011
2009 College Station second cut	starch (g kg^{-1}) = 149.794 + 0.004*applied nitrogen (kg N ha^{-1})	0.004	0.915
2010 College Station multicut first cut	starch (g kg^{-1}) = 151.429 - 0.303*applied nitrogen (kg N ha^{-1})	0.774	0.021
2010 College Station multi-cut second cut	starch (g kg^{-1}) = 136.933 - 0.192*applied nitrogen (kg N ha^{-1})	0.634	0.058
2010 College Station single-cut	starch (g kg^{-1}) = 140.373 - 0.088*applied nitrogen (kg N ha^{-1})	0.554	0.034
2010 China multicut first cut	starch (g kg^{-1}) = 112.518 + 0.020*applied nitrogen (kg N ha^{-1}) - 0.00317*applied nitrogen (kg N ha^{-1})^2	0.735	0.265
2010 China single cut	starch (g kg^{-1}) = 127.9 – 0.075*applied nitrogen (kg N ha^{-1})	0.588	0.027

Table 24. Regression of starch concentration of the above ground sorghum biomass against tissue nitrogen concentration by harvest

Harvest	Equation	r^2	p-value
2008 College Station	starch (g kg^{-1}) = 151.394 - 2.724*tissue nitrogen (g kg^{-1})	0.014	0.196
2009 College Station first cut	starch (g kg^{-1}) = 234.117 - 7.074*tissue nitrogen (g kg^{-1})	0.098	0.001
2009 College Station second cut	starch (g kg^{-1}) = 109.807 + 4.431*tissue nitrogen (g kg^{-1})	0.031	0.056
2010 College Station multicut first cut	starch (g kg^{-1}) = 156.664 - 3.383*tissue nitrogen (g kg^{-1})	0.014	0.354
2010 College Station multi-cut second cut	starch (g kg^{-1}) = 244.333 - 10.021*tissue nitrogen (g kg^{-1})	0.269	<.0001
2010 College Station single-cut	starch (g kg^{-1}) = 245.918 - 14.478*tissue nitrogen (g kg^{-1})	0.442	<.0001
2010 China multicut first cut	starch (g kg^{-1}) = 168.181 - 7.497*tissue nitrogen (g kg^{-1})	0.101	0.013
2010 China single cut	starch (g kg^{-1}) = 195.175 - 10.146*tissue nitrogen (g kg^{-1})	0.262	<.0001

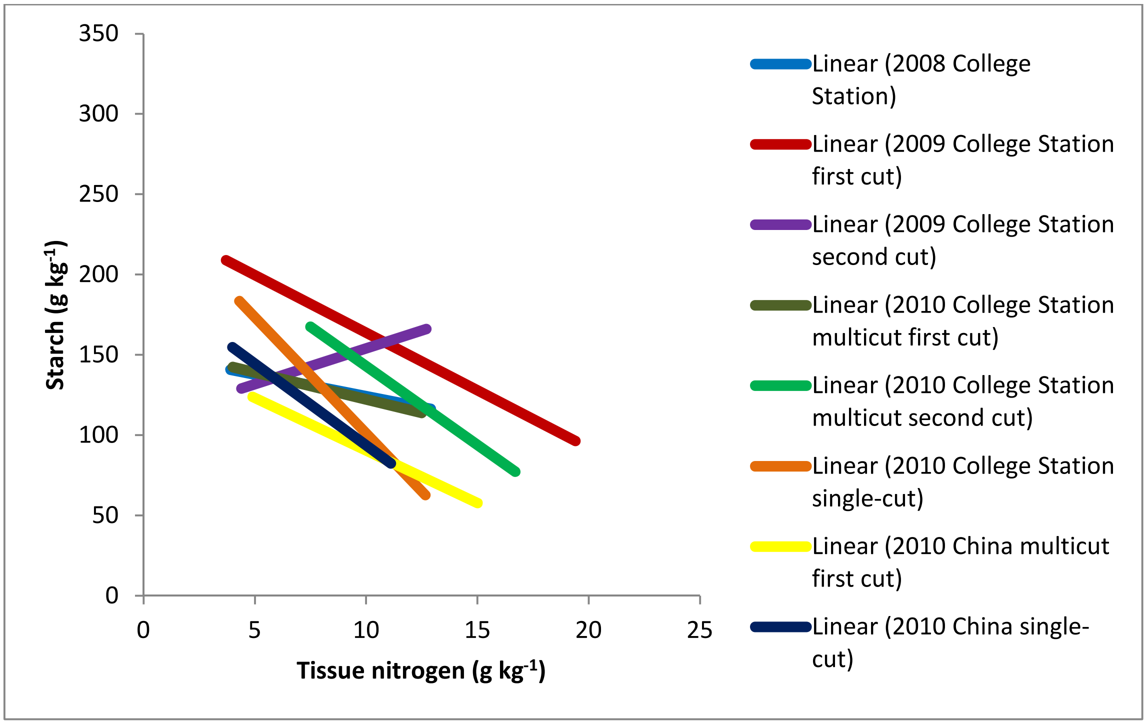

Figure 9. Regression of starch concentration of the above ground sorghum biomass against tissue nitrogen concentration by harvest

Xylans

Fertilizer treatment had little effect on the xylan concentrations since only 3 harvests showed a significant difference in concentrations among the different levels of nitrogen applications (Table 7). Where there was significance, the xylan concentrations tended to increase with tissue nitrogen and with increasing levels of nitrogen fertilizer added (Table 25, 26, 27, Figure 10). The trend was strongest in the 2010 College Station single-cut study, where there was significance and r^2s were high for both fertilizer nitrogen and tissue nitrogen and also for the whole data. The lowest concentration of xylan was found either when no fertilizer was given or with the lowest level of fertilization. The lowest mean concentration of xylan was found in the 2008 study at no fertilization at 144.62 g kg^{-1}. This study also had the lowest concentrations of xylan in general. The highest concentration was found in the 2010 China single-cut study at 176.16g kg^{-1} at 196kg N ha^{-1}. This study had the highest concentrations of xylan in general. The first harvest of the 2010 College Station multi-cut study had the biggest range in xylan concentration from 146.37 to 165.55 g kg^{-1} xylan associated with the lowest and highest levels of fertilization, respectively.

Table 25. Regression of xylan concentration of the above ground sorghum biomass against applied nitrogen rates by harvest

Harvest	Equation	r^2	p-value
2008 College Station	xylan (g kg^{-1}) = 144.726 + 0.011*applied nitrogen (kg N ha^{-1})	0.012	0.225
2009 College Station first cut	xylan (g kg^{-1}) = 146.296 + 0.009*applied nitrogen (kg N ha^{-1})	0.006	0.411
2009 College Station second cut	xylan (g kg^{-1}) = 149.006 + 0.005*applied nitrogen (kg N ha^{-1})	0.005	0.454
2010 College Station multicut first cut	xylan (g kg^{-1}) = 144.209 + 0.061*applied nitrogen (kg N ha^{-1})	0.095	0.013
2010 College Station multi-cut second cut	xylan (g kg^{-1}) = 153.503 - 0.008*applied nitrogen (kg N ha^{-1})	0.001	0.780
2010 College Station single-cut	xylan (g kg^{-1}) = 160.064 + 0.020*applied nitrogen (kg N ha^{-1})	0.038	0.058
2010 China multicut first cut	xylan (g kg^{-1}) = 159.178 + 0.003*applied nitrogen (kg N ha^{-1})	0.000	0.920
2010 China single cut	xylan (g kg^{-1}) = 169.216 + 0.023*applied nitrogen (kg N ha^{-1})	0.055	0.022

Table 26. Regression of mean xylan concentration of the above ground sorghum biomass against applied nitrogen rates by harvest

Harvest	Equation	r^2	p-value
2008 College Station	xylan (g kg^{-1}) = 144.725 + 0.011*applied nitrogen (kg N ha^{-1})	0.576	0.137
2009 College Station first cut	xylan (g kg^{-1}) = 146.182 + 0.010*applied nitrogen (kg N ha^{-1})	0.864	0.022
2009 College Station second cut	xylan (g kg^{-1}) = 149.006 + 0.005*applied nitrogen (kg N ha^{-1})	0.115	0.576
2010 College Station multicut first cut	xylan (g kg^{-1}) = 143.532 + 0.077*applied nitrogen (kg N ha^{-1})	0.786	0.019
2010 College Station multi-cut second cut	xylan (g kg^{-1}) = 152.406 + 0.021*applied nitrogen (kg N ha^{-1})	0.191	0.386
2010 College Station single-cut	xylan (g kg^{-1}) = 160.063 + 0.020*applied nitrogen (kg N ha^{-1})	0.547	0.036
2010 China multicut first cut	xylan (g kg^{-1}) = 161.459 - 0.015*applied nitrogen (kg N ha^{-1})	0.109	0.587
2010 China single cut	xylan (g kg^{-1}) = 169.217 + 0.023*applied nitrogen (kg N ha^{-1})	0.704	0.009

Table 27. Regression of xylan concentration of the above ground sorghum biomass against tissue nitrogen concentration by harvest

Harvest	Equation	r^2	p-value
2008 College Station	xylan (g kg^{-1}) = 143.906 + 0.215*tissue nitrogen (g kg^{-1})	0.005	0.430
2009 College Station first cut	xylan (g kg^{-1}) = 144.909 + 0.240*tissue nitrogen (g kg^{-1})	0.009	0.313
2009 College Station second cut	xylan (g kg^{-1}) = 150.212 - 0.085*tissue nitrogen (g kg^{-1})	0.001	0.763
2010 College Station multicut first cut	xylan (g kg^{-1}) = 157.272 - 0.864*tissue nitrogen (g kg^{-1})	0.011	0.401
2010 College Station multi-cut second cut	xylan (g kg^{-1}) = 139.583 + 1.162*tissue nitrogen (g kg^{-1})	0.064	0.051
2010 College Station single-cut	xylan (g kg^{-1}) = 129.031 + 4.150*tissue nitrogen (g kg^{-1})	0.623	<.0001
2010 China multicut first cut	xylan (g kg^{-1}) = 147.839 + 1.387*tissue nitrogen (g kg^{-1})	0.050	0.086
2010 China single cut	xylan (g kg^{-1}) = 154.596 + 2.330*tissue nitrogen (g kg^{-1})	0.167	<.0001

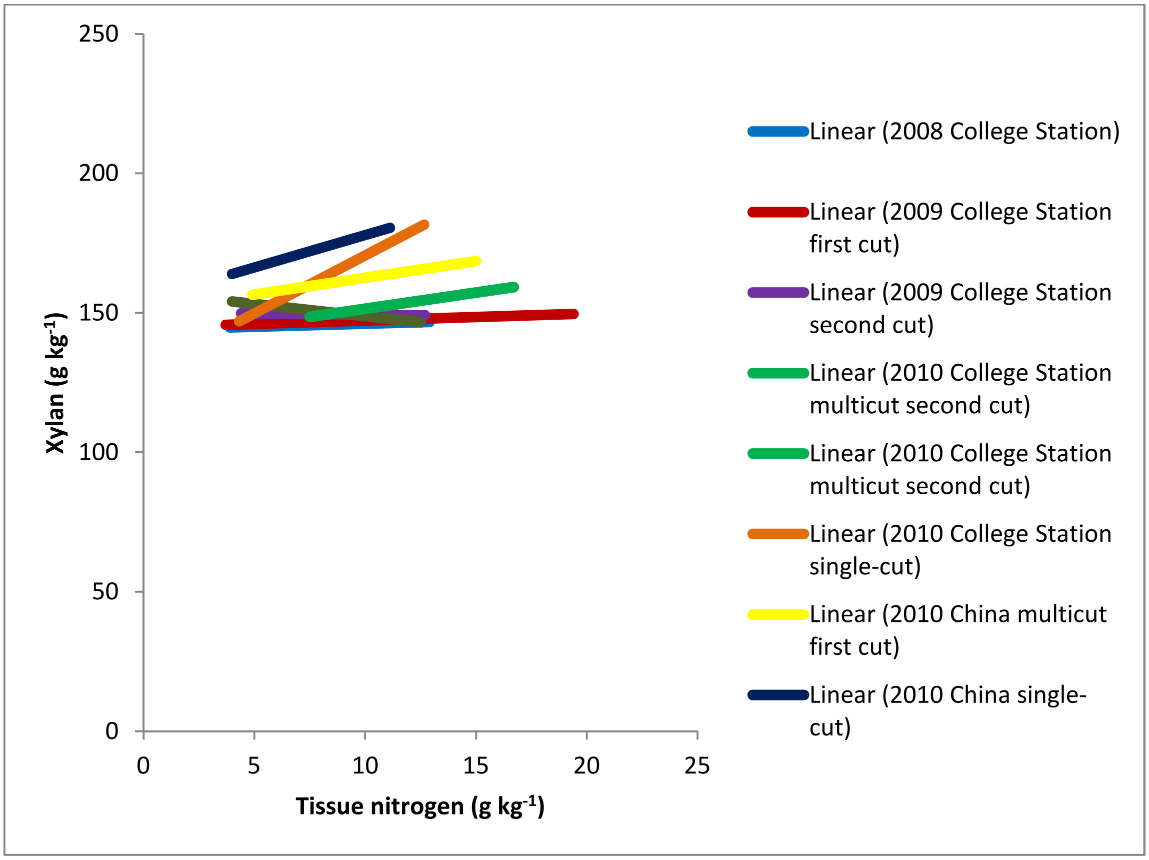

Figure 10. Regression of xylan concentration of the above ground sorghum biomass against tissue nitrogen concentration by harvest

Cellulose

Generally, the relationship of cellulose concentration with tissue nitrogen tended to be positive just as in the case of xylan (Figure 11). Similarities with xylan were expected since both cellulose and xylan are polysaccharides that are used in forming cell walls. Compared to xylan, the relationships with tissue nitrogen and applied nitrogen were even weaker and it can't be said that the significance was only found with positive relationships (Table 29 and 30). According to the analysis of variance, only one harvest, the 2010 College Station single-cut study, had a significant treatment effect on cellulose (Table 7). Similarly to xylan, the 2010 College Station single-cut study had the best trends which were positive and had high r^2s but lower than those for xylan. Based on these results, it seemed that nitrogen application had very little or no effect on biomass cellulose concentrations within the harvests of this project.

Table 28. Regression of cellulose concentration of the above ground sorghum biomass against applied nitrogen rates by harvest

Harvest	Equation	r^2	p-value
2008 College Station	cellulose (g kg^{-1}) = 235.736 + 0.012*applied nitrogen (kg N ha^{-1})	0.005	0.453
2009 College Station first cut	cellulose (g kg^{-1}) = 242.973 + 0.013*applied nitrogen (kg N ha^{-1})	0.003	0.570
2009 College Station second cut	cellulose (g kg^{-1}) = 249.772 + 0.002*applied nitrogen (kg N ha^{-1})	>.001	0.873
2010 College Station multicut first cut	cellulose (g kg^{-1}) = 225.602 + 0.163*applied nitrogen (kg N ha^{-1})	0.097	0.012
2010 College Station multi-cut second cut	cellulose (g kg^{-1}) = 260.896 - 0.037*applied nitrogen (kg N ha^{-1})	0.005	0.609
2010 College Station single-cut	cellulose (g kg^{-1}) = 275.476 + 0.036*applied nitrogen (kg N ha^{-1})	0.026	0.116
2010 China multicut first cut	cellulose (g kg^{-1}) = 271.543 - 0.033*applied nitrogen (kg N ha^{-1})	0.004	0.628
2010 China single cut	cellulose (g kg^{-1}) = 288.202 + 0.045*applied nitrogen (kg N ha^{-1})	0.032	0.080

Table 29. Regression of mean cellulose concentration of the above ground sorghum biomass against applied nitrogen rate by harvest

Harvest	Equation	r^2	p-value
2008 College Station	cellulose (g kg^{-1}) = 235.733 + 0.012*applied nitrogen (kg N ha^{-1})	0.188	0.466
2009 College Station first cut	cellulose (g kg^{-1}) = 242.678 + 0.016*applied nitrogen (kg N ha^{-1})	0.583	0.133
2009 College Station second cut	cellulose (g kg^{-1}) = 249.774 + 0.002*applied nitrogen (kg N ha^{-1})	0.007	0.894
2010 College Station multicut first cut	cellulose (g kg^{-1}) = 223.818 + 0.202*applied nitrogen (kg N ha^{-1})	0.794	0.017
2010 College Station multi-cut second cut	cellulose (g kg^{-1}) = 258.972 + 0.015*applied nitrogen (kg N ha^{-1})	0.023	0.775
2010 College Station single-cut	cellulose (g kg^{-1}) = 275.478 + 0.036*applied nitrogen (kg N ha^{-1})	0.379	0.104
2010 China multicut first cut	cellulose (g kg^{-1}) = 276.534 - 0.072*applied nitrogen (kg N ha^{-1})	0.375	0.272
2010 China single cut	cellulose (g kg^{-1}) = 288.200 + 0.045*applied nitrogen (kg N ha^{-1})	0.512	0.046

Table 30. Regression of cellulose concentration of the above ground sorghum biomass against tissue nitrogen concentration by harvest

Harvest	Equation	r^2	p-value
2008 College Station	cellulose (g kg^{-1}) = 242.204 - 0.707*tissue nitrogen (g kg^{-1})	0.017	0.151
2009 College Station first cut	cellulose (g kg^{-1}) = 243.991 + 0.008*tissue nitrogen (g kg^{-1})	<.0001	0.986
2009 College Station second cut	cellulose (g kg^{-1}) = 258.377 - 0.925*tissue nitrogen (g kg^{-1})	0.021	0.113
2010 College Station multicut first cut	cellulose (g kg^{-1}) = 273.161 - 3.768*tissue nitrogen (g kg^{-1})	0.031	0.161
2010 College Station multi-cut second cut	cellulose (g kg^{-1}) = 230.426 + 2.454*tissue nitrogen (g kg^{-1})	0.046	0.099
2010 College Station single-cut	cellulose (g kg^{-1}) = 216.878 + 7.821*tissue nitrogen (g kg^{-1})	0.450	<.0001
2010 China multicut first cut	cellulose (g kg^{-1}) = 247.060 + 2.622*tissue nitrogen (g kg^{-1})	0.028	0.198
2010 China single cut	cellulose (g kg^{-1}) = 261.456 + 4.308*tissue nitrogen (g kg^{-1})	0.090	0.003

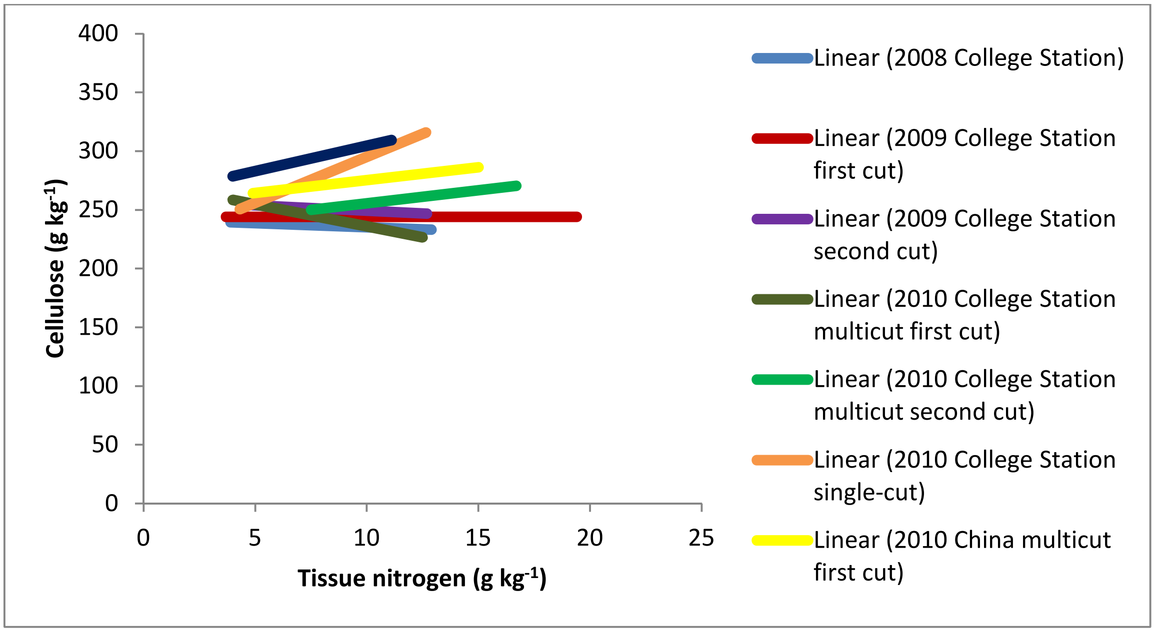

Figure 11. Regression of cellulose concentration of the above ground sorghum biomass and tissue nitrogen concentration by harvest

Lignin

According to the analysis of variance, lignin concentration was affected by nitrogen application in 6 out of 8 harvests (Table 7). Lignin had a positive relationship with tissue nitrogen and fertilizer nitrogen in every case where this relationship was found to be significant. The regression between lignin and applied nitrogen was significant at the 0.05 level in 3 harvests for the whole dataset and 4 harvests for means data and was significant at the 0.1 level for 4 harvests for the whole dataset and 5 harvests for the means data (Table 31 and 32). The correlation between lignin and tissue nitrogen concentration was significant in 4 harvests at the 0.05 level and in 5 harvests at the 0.1 level (Table 33). The strongest relationships were found in the two single-cut studies where the r^2s were high and the slope was strongly significant. There we saw a sharp increase in lignin in relation with tissue nitrogen. The increase was around 12 to 16 g kg^{-1} when looking at data averaged over nitrogen levels (Figure 12). When looking at the whole dataset, the range was higher, about a 30 to 40g kg^{-1} increase. The rest of the harvests had more moderate slopes and the r^2s were also lower. In this case, the studies with the most levels of nitrogen treatment showed the best results.

Table 31. Regression of lignin concentration of the above ground sorghum biomass against applied nitrogen rates by harvest

Harvest	Equation	r^2	p-value
2008 College Station	lignin (g kg^{-1}) = 99.089 + 0.024*applied nitrogen (kg N ha^{-1})	0.019	0.132
2009 College Station first cut	lignin (g kg^{-1}) = 79.122 + 0.044*applied nitrogen (kg N ha^{-1})	0.043	0.023
2009 College Station second cut	lignin (g kg^{-1}) = 86.077 + 0.007*applied nitrogen (kg N ha^{-1})	0.005	0.455
2010 College Station multicut first cut	lignin (g kg^{-1}) = 102.864 + 0.077*applied nitrogen (kg N ha^{-1})	0.05	0.075
2010 College Station multi-cut second cut	lignin (g kg^{-1}) = 76.801 + 0.054*applied nitrogen (kg N ha^{-1})	0.027	0.207
2010 College Station single-cut	lignin (g kg^{-1}) = 83.246 + 0.039*applied nitrogen (kg N ha^{-1})	0.046	0.036
2010 China multicut first cut	lignin (g kg^{-1}) = 107.595 + 0.052*applied nitrogen (kg N ha^{-1})	0.012	0.409
2010 China single cut	lignin (g kg^{-1}) = 97.542 + 0.053*applied nitrogen (kg N ha^{-1})	0.137	0.0002

Table 32. Regression of mean lignin concentration of the above ground sorghum biomass against applied nitrogen rate by harvest

Harvest	Equation	r^2	p-value
2008 College Station	lignin (g kg^{-1}) = 99.089 + 0.024*applied nitrogen (kg N ha^{-1})	0.593	0.128
2009 College Station first cut	lignin (g kg^{-1}) = 79.024 + 0.045*applied nitrogen (kg N ha^{-1})	0.916	0.011
2009 College Station second cut	lignin (g kg^{-1}) = 86.074 + 0.007*applied nitrogen (kg N ha^{-1})	0.281	0.358
2010 College Station multicut first cut	lignin (g kg^{-1}) = 101.251 + 0.111*applied nitrogen (kg N ha^{-1})	0.619	0.063
2010 College Station multi-cut second cut	lignin (g kg^{-1}) = 75.101 + 0.100*applied nitrogen (kg N ha^{-1})	0.749	0.026
2010 College Station single-cut	lignin (g kg^{-1}) = 83.246 + 0.039*applied nitrogen (kg N ha^{-1})	0.550	0.035
2010 China multicut first cut	lignin (g kg^{-1}) = 112.744 + 0.012*applied nitrogen (kg N ha^{-1})	0.019	0.823
2010 China single cut	lignin (g kg^{-1}) = 97.538 + 0.053*applied nitrogen (kg N ha^{-1})	0.784	0.003

Table 33. Regression of lignin concentration of the above ground sorghum biomass against tissue nitrogen by harvest

Harvest	Equation	r^2	p-value
2008 College Station	lignin (g kg^{-1}) = 93.449 + 0.971*tissue nitrogen (g kg^{-1})	0.033	0.049
2009 College Station first cut	lignin (g kg^{-1}) = 70.331 + 1.375*tissue nitrogen (g kg^{-1})	0.099	0.001
2009 College Station second cut	lignin (g kg^{-1}) = 89.471 - 0.307*tissue nitrogen (g kg^{-1})	0.005	0.430
2010 College Station multicut first cut	lignin (g kg^{-1}) = 112.854 - 0.357*tissue nitrogen (g kg^{-1})	0.001	0.840
2010 College Station multi-cut second cut	lignin (g kg^{-1}) = 60.007 + 1.700*tissue nitrogen (g kg^{-1})	0.063	0.052
2010 College Station single-cut	lignin (g kg^{-1}) = 38.144 + 6.203*tissue nitrogen (g kg^{-1})	0.432	<.0001
2010 China multicut first cut	lignin (g kg^{-1}) = 96.006 + 1.899*tissue nitrogen (g kg^{-1})	0.017	0.324
2010 China single cut	lignin (g kg^{-1}) = 65.460 + 5.153*tissue nitrogen (g kg^{-1})	0.389	<.0001

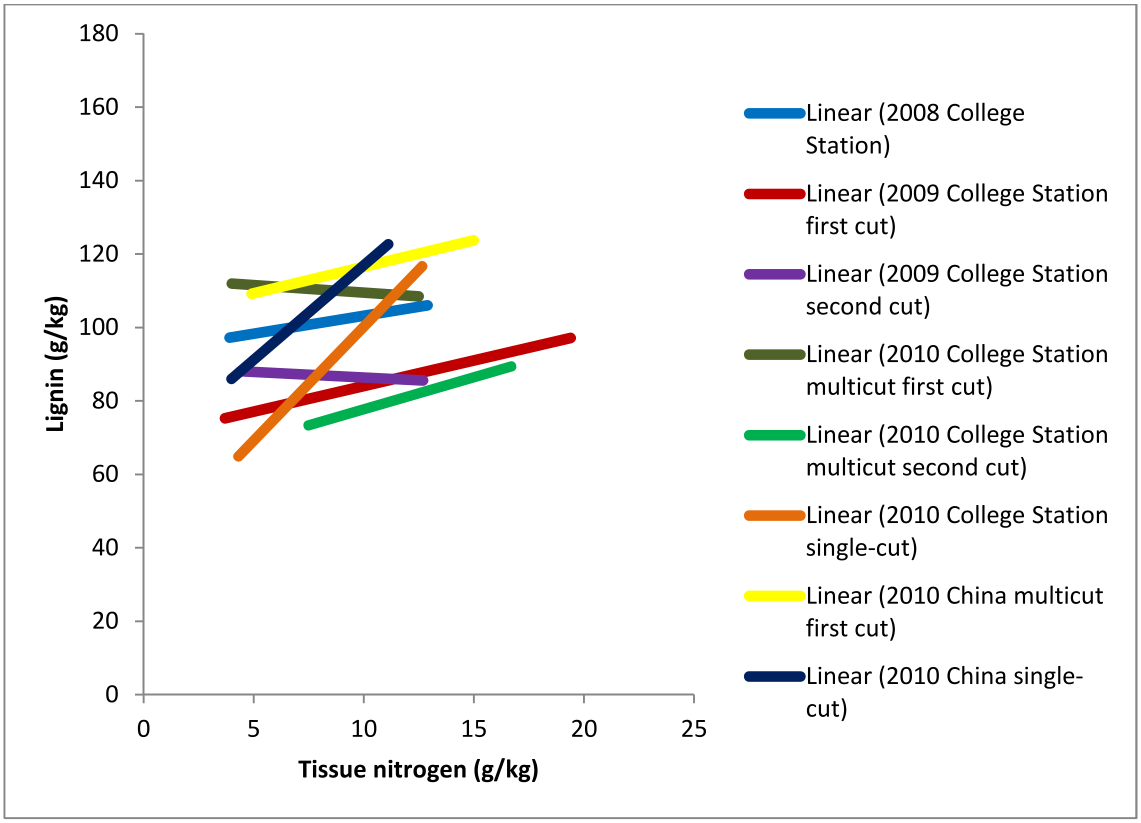

Figure 12. Regression of lignin concentration of the above ground sorghum biomass and tissue nitrogen concentration by harvest

SUMMARY OF RESULTS

During this study it was generally observed that changes in biomass tissue quality correlated well with changes in tissue nitrogen. This was especially true for ash and sucrose content, where ash increased and sucrose consistently and significantly decreased with an increase in tissue nitrogen concentration. These relationships were also significant with fertilizer nitrogen rate in most trials. Lignin was also shown to increase with tissue nitrogen concentration although the relationship was weaker than in the cases of ash and sucrose. Cellulose and xylan had very weak correlations with tissue nitrogen concentration. For both compounds, there was a slightly increasing trend, but overall nitrogen fertilization and the changes in tissue nitrogen didn't have a major impact on them. From the data, it seems like cellulose and xylan concentrations were better predicted by each other. Starch also tended to decrease with tissue nitrogen. This could be seen most pronouncedly in the two single-cut studies, where there were 8 nitrogen rates instead of five. It can be seen that starch also tends to follow a similar trend to sucrose.

Nitrogen fertilization proved to be a good predictor of tissue nitrogen concentration in most cases. In most harvests, fertilizer nitrogen rates and tissue nitrogen concentration had similar predictive value for the observed quality components with tissue nitrogen concentration being somewhat more reliable predictor. The reason for this is that the observed quality components probably correlated with how much nitrogen the plant takes up and not directly with how much nitrogen is applied. Since nitrogen availability and uptake depend on more than one factor, tissue nitrogen concentration was the best indicator of it.

ECONOMIC IMPLICATIONS

Introduction

This study does not have data regarding current and possible future market conditions for biomass sorghum. In the real world, management practices that impact yield and tissue quality are only relevant in light of market demands. Depending on selling prices it may or may not be profitable to increase yield beyond a certain point. Whether some deterioration in tissue quality is a problem for the grower is also determined by how it affects the selling price. Therefore, the following is a brief discussion about the economics of fertilizing biomass feedstocks.

Economics of fertilizing biomass feedstocks

Ignoring risk and uncertainty, the classic economic principles of concern when evaluating how much fertilizer to apply to a feedstock crop are diminishing returns and marginalism (Johnson 2005, Rhoads 2011). Diminishing returns relates to the phenomena that as more and more of a variable input (e.g., fertilizer nutrient) is added to a set of fixed production inputs (e.g., an acre of land of specified quality, an established population of the biomass feedstock crop, the existing soil moisture profile, existing nutrient levels in the soil, etc.), in a classic sense, the yield response will first increase at an increasing rate per unit of added fertilizer nutrient (Stage 1), then increase at a diminishing rate (Stage 2), and eventually total yield will decline as too much of the variable input is added relative to the levels of the fixed input (Stage 3).

It is within stage 2 of this classic production function that the most profitable level of production occurs as defined by the marginalism principles: (1) from an input perspective, add another unit of the variable input (e.g., fertilizer nutrient) so long as the per unit added (marginal) cost of that input is exceeded by the value of the additional (marginal) output (e.g., biomass feedstock) produced with the added input and/or (2) from an output perspective, produce another unit of output (e.g., biomass feedstock) so long as the added (marginal) value of producing that added output exceeds the added costs associated with adding the amount of variable input (e.g., fertilizer nutrient) required to realized the added production.

The above admittedly simplified (because it ignores risk and uncertainty) economic paradigm is indicative of three basic elements of information being required to identify the profit-maximizing level of fertilizer nutrient to apply to a biomass feedstock crop:

(1) the biomass feedstock yield response relationship with applied fertilizer nutrients, with nitrogen being the most critical nutrient of interest in this research;

(2) the per unit cost of fertilizer nutrients; and

(3) the per unit value of biomass feedstocks.

Information for (1) is associated with the agronomic experiments presented and discussed previously in this thesis. So far as item (2) is concerned, contemporary farm-level nitrogen prices are $1.00-$1.30 per kilogram of nitrogen (USDA 2011). In regards to item (3), with no established local markets for biomass feedstocks in Texas, it is somewhat difficult to identify the value of the feedstock output. However, several economic studies have been published indicating the apparent cost per unit of biomass feedstock delivered to a cellulosic conversion facility(Foust et al. 2009; Tao and Aden, 2009) with such cost estimates ranging from ($32.00 to $150.00+ per ton). Such cost estimates can be considered proxies for the value of biomass feedstock and used in sensitivity analyses to ascertain what might be the optimal applied nitrogen levels under various specified sets of circumstances (Jensen, 2008).

Biomass feedstock yield response to applied nitrogen: An example

To show a possible way of calculating the amount of fertilizer with which profitable yields can still be achieved, marginal value product was calculated based on theoretical biomass selling prices (Table 36.). The first harvest of 2009 was used for this example. First a regression curve was calculated for yield with the variables applied nitrogen and the square of applied nitrogen (Figure 13, Table 34). For simplicity's sake the variety effect was not used. Then marginal physical product was calculated by dividing the difference between yield at a higher and lower nitrogen level and with the difference of the two nitrogen levels (Table 35). This results in the amount of additional biomass in Mg ha^{-1} that can be reached by adding an extra unit of nitrogen fertilizer based on the calculated response curve. Using these values, we calculated the marginal value products for the different theoretical market prices at different rates of nitrogen fertilization (Table 36). The marginal value product tells us the price in dollars for additional yield per extra nitrogen. Comparing the marginal value products to the current price of fertilizer can tell us whether based on this scenario it would be profitable to add extra nitrogen to increase yield or not.

Table 34. Parameter estimates of yield response predicted by applied nitrogen rate and the square values of applied nitrogen rate for the based on the first harvest of 2009

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	9.64198	0.49445	19.5	<.0001
N-rate (N kg ha^{-1})	0.03684	0.01394	2.64	0.0093
N-rate^2 (N kg ha^{-1})	-0.00020228	0.00007948	-2.55	0.0122

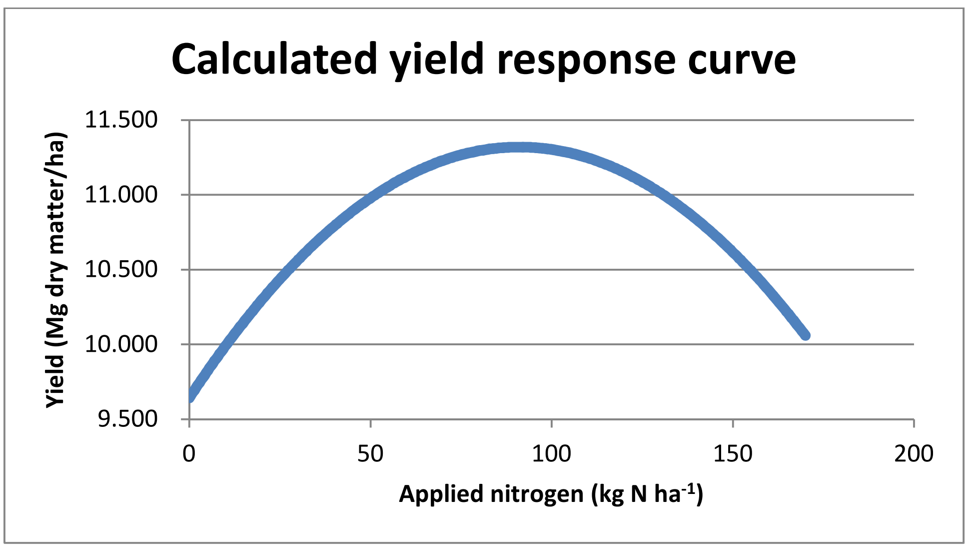

Figure 13. Calculated yield response curve based on data from the first harvest of 2009 using N-rate and the squared values of nitrogen rate as independent variables

Table 35. Marginal physical product calculated from the ratio of calculated yield change over unit increase in N fertilizer application

N-rate (N kg ha^{-1})	Calculated yield response (Mg ha^{-1})	Marginal physical product (Mg ha^{-1} kg^{-1} of N)
0	9.642	
10	9.990	0.03482
20	10.298	0.03077
30	10.565	0.02673
40	10.792	0.02268
50	10.978	0.01863
60	11.124	0.01459
70	11.230	0.01054
80	11.295	0.00650
90	11.319	0.00245
100	11.303	-0.00159
110	11.247	-0.00564
120	11.150	-0.00968
130	11.013	-0.01373
140	10.835	-0.01778
150	10.617	-0.02182
160	10.358	-0.02587
170	10.059	-0.02991

Table 36. Marginal value products calculated for 6 different hypothetical selling prices. The green areas indicate that adding an extra unit of nitrogen is still profitable, the red areas indicate that yield increase achieved by adding extra nitrogen does not pay for the added cost of fertilizer at a fertilizer price of $1.32/kg N.

	Hypothetical selling price per metric ton					
N-rate (N kg ha^{-1})	$ 30.00	$ 50.00	$ 75.00	$ 100.00	$ 125.00	$ 150.00
	MVP30	MVP50	MVP75	MVP100	MVP125	MVP150
	Marginal Value Product: Price in dollars for additional yield per extra kg of nitrogen at each selling price (Dollar value of additional yield per kg of N applied)					
0	1.15137	1.91895	2.87842	3.83790	4.79737	5.75685
10	1.01759	1.69598	2.54397	3.39195	4.23994	5.08793
20	0.88380	1.47300	2.20951	2.94601	3.68251	4.41901
30	0.75002	1.25003	1.87505	2.50006	3.12508	3.75009
40	0.61623	1.02706	1.54059	2.05411	2.56764	3.08117
50	0.48245	0.80408	1.20613	1.60817	2.01021	2.41225
60	0.34867	0.58111	0.87167	1.16222	1.45278	1.74333
70	0.21488	0.35814	0.53721	0.71627	0.89534	1.07441
80	0.08110	0.13516	0.20275	0.27033	0.33791	0.40549
90	-0.05269	-0.08781	-0.13171	-0.17562	-0.21952	-0.26343
100	-0.18647	-0.31078	-0.46617	-0.62156	-0.77696	-0.93235
110	-0.32025	-0.53376	-0.80063	-1.06751	-1.33439	-1.60127
120	-0.45404	-0.75673	-1.13509	-1.51346	-1.89182	-2.27019
130	-0.58782	-0.97970	-1.46955	-1.95940	-2.44926	-2.93911
140	-0.72161	-1.20268	-1.80401	-2.40535	-3.00669	-3.60803
150	-0.85539	-1.42565	-2.13847	-2.85130	-3.56412	-4.27695
160	-0.98917	-1.64862	-2.47293	-3.29724	-4.12155	-4.94587

CONCLUSIONS

It was observed that tissue nitrogen concentration correlates better with quality components than applied nitrogen rates. The effects of nitrogen rates didn't show any significant correlation with the amount of nitrogen taken up by the crop in 3 out of the 8 harvests. The concentrations of quality components showed slightly better correlations with tissue nitrogen than with applied nitrogen rates. For this reason we could speculate that the level of tissue nitrogen might influence the production of some of these components. But all we can say confidently based on this research is that when the tissue nitrogen concentration changes, so do some of the aspects of tissue quality. Since applying more nitrogen fertilizer was found to increase tissue nitrogen concentration, it is safe to say that nitrogen fertilization has an effect on the tissue quality of sorghum. The results of this study were similar to most of the results found in other studies. The increase of tissue nitrogen with applied nitrogen rates has been observed in crops like sorghum, corn, durum wheat and ryegrass (Almodares et al 2009, Keady et al 2000, De Giorgio et al 2008). The decrease of sucrose with the increase of nitrogen rate and tissue nitrogen was a result that was expected based on a similar study performed on corn and sorghum mentioned in the literature review. (Almodares et al., 2009), The increase of ash and lignin with tissue nitrogen concentration and nitrogen rate was also expected based on other studies (Li et al., 2010; Marino et al.,). These trends are not universal to all species for example in giant reed ash decreased with the increase of tissue nitrogen and in poplar lignin decreased. In corn and wheat however the trends were similar to those found during this research.

Knowing how fertilization affects the tissue quality of sorghum may be important depending on the type of conversion that will be predominantly used to convert the biomass into fuel. In case of a thermochemical conversion method, a high ash content can pose significant challenges. Whereas in case of biological conversion the decrease in sucrose and the increase in lignin concentration could lower the efficiency of conversion. The increase in yield that is achieved by nitrogen fertilization might still outweigh the possible negative effects on tissue quality depending on the market price.

However it is more likely that the selling price of biofuel crops will not be high enough to warrant trying to reach maximum yields.

The economic example given in this study is a very simplified model for trying to determine the optimum level of fertilization. It only used data from one harvest and had only one independent variable. In the future more robust models could be built by analyzing data from multiple years, locations, and harvests. The variety effect, distance from conversion facility and the price of fuel burnt in transport and field maintenance could also be added to calculate profitability of fertilizing at hypothetical selling prices. Models could also be built in which the theoretical selling price rises or falls with changes in tissue quality components such as sucrose or ash. Calculating for such scenarios for a variety of crops is already the subject of several studies in the field of agricultural economics and leaves much research to be done in the future as well.

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APPENDIX A

ANOVA Tables

Table A1. Analysis of variance for dependent variables: yield, tissue nitrogen, ash, sucrose, xylan, cellulose, lignin and starch based on data from the 2008 College Station harvest

	Yield			Tissue nitrogen		Ash	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	32	17.470036	0.114	7.9568854	<.0001	95.380487	<.0001
N-rate	4	15.4142744	0.3038	5.9980417	0.0376	31.022814	0.3457
Variety	5	36.4417289	0.0178	12.4985333	0.0002	430.613938	<.0001
Rep	3	2.3890112	0.9025	41.4468889	<.0001	92.314938	0.0219
N-rate*var	20	15.4004186	0.2509	2.1897417	0.5010	24.903491	0.5751
Error	87	12.525504		2.2493602			
Total	119						

	Sucrose			Xylan		Cellulose	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	32	1651.01899	<.0001	98.823604	<.0001	295.71059	<.0001
N-rate	4	719.7695	0.0454	21.316362	0.0558	82.848126	0.0912
Variety	5	7828.70894	<.0001	562.408942	<.0001	1554.970732	<.0001
Rep	3	1102.83694	0.0116	0.349465	0.9895	105.764665	0.054
N-rate*var	20	375.0737	0.186	13.199838	0.1063	51.959935	0.201
Error	87	283.21125		8.869796		39.95869	
Total	119						

	Lignin			Starch
Source	df	Mean square	Pr>F	Mean square
Model	32	345.26345	<.0001	6143.0488
N-rate	4	105.482597	0.0022	1553.9047
Variety	5	1720.587407	<.0001	33498.2407
Rep	3	188.131959	<.0001	231.4698
N-rate*var	20	72.958355	0.0001	1108.8164
Error	87	23.21548		455.6077
Total	119			

Table A2. Analysis of variance for dependent variables: yield, tissue nitrogen, ash, sucrose, xylan, cellulose, lignin and starch based on data from the first harvest of 2009 in College Station

	Yield			Tissue nitrogen		Ash	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	32	10.2823034	0.0153	16.2715815	<.0001	169.326103	<.0001
N-rate	4	11.723189	0.0914	90.4542367	<.0001	521.388162	<.0001
Variety	5	37.8747513	<.0001	8.3238408	0.1721	505.9153	<.0001
Rep	3	4.3253517	0.5171	1.6604075	0.8133	78.338205	0.0949
N-rate*var	20	3.9895571	0.811	5.6136617	0.3943	28.414577	0.7133
Error	87	5.659455		5.2437811		35.76598	
Total	119						

	Sucrose			Xylan		Cellulose	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	32	1884.18911	<.0001	162.681919	<.0001	631.16416	<.0001
N-rate	4	2374.04538	<.0001	11.817159	0.5478	42.31534	0.6526
Variety	5	8394.50898	<.0001	884.663528	<.0001	3386.65782	<.0001
Rep	3	1383.37608	0.0045	144.002334	<.0001	625.28298	<.0001
N-rate*var	20	233.75985	0.7204	15.161406	0.4848	60.94268	0.6039
Error	87	296.55139		15.351572		68.73935	
Total	119						

	Lignin			Starch
Source	df	Mean square	Pr>F	Mean square
Model	32	480.70909	<.0001	12915.7679
N-rate	4	218.91415	0.0003	5876.4298
Variety	5	2562.12601	<.0001	72442.4929
Rep	3	229.0883	0.0007	2593.0914
N-rate*var	20	50.45697	0.1611	990.3558
Error	87	36.88737		1001.7218
Total	119			

Table A3. Analysis of variance for dependent variables: yield, tissue nitrogen, ash, sucrose, xylan, cellulose, lignin and starch based on data from the second harvest of 2009 in College Station.

	Yield			Tissue nitrogen		Ash	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	32	16.6543067	<.0001	4.8411146	<.0001	80.672599	<.0001
N-rate	4	15.7127875	<.0001	13.93570833	<.0001	77.221041	<.0001
Variety	5	18.4855119	<.0001	8.43975	<.0001	379.379722	<.0001
Rep	3	108.980162	<.0001	9.59497222	<.0001	8.536701	0.3507
N-rate*var	20	2.535931	0.1792	1.40945833	0.2864	17.506514	0.0048
Error	87	1.8986136		1.1890527		7.711508	

	Sucrose			Xylan		Cellulose	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	32	1178.69588	<.0001	48.064523	<.0001	207.12265	<.0001
N-rate	4	66.19588	0.6159	24.6963118	0.0481	81.099889	0.1277
Variety	5	6870.40214	<.0001	174.1029793	<.0001	589.407648	<.0001
Rep	3	0.9989	0.9986	108.3313139	<.0001	814.378026	<.0001
N-rate*var	20	154.92387	0.081	12.1885321	0.2466	45.667651	0.4284
Error	87	99.08925		9.867449		43.98447	
Total	119						

	Lignin			Starch
Source	df	Mean square	Pr>F	Mean square
Model	32	109.242854	<.0001	2549.1232
N-rate	4	19.577066	0.2022	305.99981
Variety	5	304.136386	<.0001	12300.86348
Rep	3	557.417465	<.0001	1863.07119
N-rate*var	20	11.226437	0.619	662.72063
Error	87	12.844722		973.3417
Total	119			

Table A4. Analysis of variance for dependent variables, yield, tissue nitrogen, ash, sucrose, xylan, cellulose, lignin and starch based on data from the first harvest of the 2010 College Station multi-cut study

	Yield			Tissue nitrogen		Ash	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	18	37.350901	<.0001	3.6570139	0.1531	299.534602	<.0001
N-rate	5	28.2229236	0.0207	2.087	0.5348	131.809345	0.0219
Variety	2	165.1984938	<.0001	1.82816667	0.4887	2033.990705	<.0001
Rep	3	9.3070036	0.4085	14.20208333	0.0023	125.609185	0.0502
N-rate*var	8	21.6104502	0.038	1.14108333	0.8814	35.970894	0.6021
Error	45	9.451624		2.51275		44.721174	
Total	63						

	Sucrose			Xylan		Cellulose	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	18	4593.14868	<.0001	564.13303	<.0001	3830.87552	<.0001
N-rate	5	1718.54466	<.0001	295.894636	<.0001	2051.81606	<.0001
Variety	2	33249.18788	<.0001	4069.322865	<.0001	26460.15176	<.0001
Rep	3	1116.86268	0.005	54.057142	0.2039	1132.4134	0.0092
N-rate*var	8	529.37365	0.0357	46.763033	0.2314	297.39192	0.3586
Error	45	228.56576		33.90211		261.86152	
Total	63						

Source	Lignin			Starch
	df	Mean square	Pr>F	Mean square
Model	18	1689.60126	<.0001	7515.6876
N-rate	5	697.27571	<.0001	4699.4046
Variety	2	12132.32421	<.0001	53132.692
Rep	3	617.09503	0.0007	234.4463
N-rate*var	8	101.31383	0.3732	602.0788
Error	45	91.08295		272.2072
Total	63			

Table A5. Analysis of variance for dependent variables, yield, tissue nitrogen, ash, sucrose, xylan, cellulose, lignin and starch based on data from the second harvest of the 2010 College Station multi-cut study

Source	Yield			Tissue nitrogen		Ash	
	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	17	4.2908072	0.0149	7.7628792	0.0007	106.551211	<.0001
N-rate	4	4.65809051	0.058	16.73274	0.0002	93.849076	0.0111
Variety	2	3.88291096	0.1387	19.00014	0.001	646.023815	<.0001
Rep	3	3.02536803	0.2005	6.80352889	0.0441	34.984297	0.2597
N-rate*var	8	4.68367934	0.0257	0.82839	0.9367	4.871721	0.9904
Error	42	1.8747305		2.3154575		25.208298	
Total	59						

Source	Sucrose			Xylan		Cellulose	
	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	17	1442.89993	<.0001	184.556199	<.0001	1059.73631	0.0003
N-rate	4	428.78661	0.1522	49.531039	0.3128	336.49162	0.3303
Variety	2	10491.66777	<.0001	1269.844718	<.0001	6957.3546	<.0001
Rep	3	24.21029	0.9595	9.902179	0.8638	165.51444	0.6288
N-rate*var	8	219.77325	0.5184	46.241907	0.3526	282.28729	0.4532
Error	42	241.79009		40.277078		283.39239	
Total	59						

	Lignin			Starch
Source	df	Mean square	Pr>F	Mean square
Model	17	312.0404	0.0071	3627.00763
N-rate	4	124.399286	0.4106	874.58413
Variety	2	1974.73705	<.0001	27636.94889
Rep	3	86.584111	0.5535	84.38782
N-rate*var	8	74.732897	0.7644	329.2165
Error	42	122.54512		572.74692
Total	59			

Table A6. Analysis of variance for dependent variables, yield, tissue nitrogen, ash, sucrose, xylan, cellulose, lignin and starch based on data from the 2010 College Station single-cut study

	Yield			Tissue nitrogen		Ash	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	26	67.466748	<.0001	8.6054476	<.0001	178.787364	<.0001
N-rate	7	75.8779034	<.0001	9.3917653	<.0001	64.980235	0.0011
Variety	2	252.1306995	<.0001	73.328712	<.0001	2008.395821	<.0001
Rep	3	33.3121131	0.074	0.336766	0.7644	25.728155	0.2046
N-rate*var	14	44.1994564	0.0006	0.7379684	0.6214	7.116693	0.9578
Error	69	13.798348		0.8754777		16.390021	
Total	95						

	Sucrose			Xylan		Cellulose	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	26	3349.9816	<.0001	220.064295	<.0001	848.49982	<.0001
N-rate	7	1025.6554	0.0003	77.713211	0.0229	380.72707	0.1539
Variety	2	35504.47898	<.0001	2347.291591	<.0001	7812.39729	<.0001
Rep	3	1793.32155	0.0001	25.507781	0.4835	225.4048	0.4264
N-rate*var	14	252.21512	0.3452	29.040905	0.5204	221.06407	0.5407
Error	69	222.2999		30.84447		239.92137	
Total	95						

	Lignin			Starch
Source	df	Mean square	Pr>F	Mean square
Model	26	655.40704	<.0001	3405.8209
N-rate	7	300.48273	0.0232	1552.99323
Variety	2	4093.587426	<.0001	32569.30977
Rep	3	1473.957675	<.0001	1296.04649
N-rate*var	14	166.296867	0.1814	618.11647
Error	69	119.56276		667.5958
Total	95			

Table A7. Analysis of variance for dependent variables, yield, tissue nitrogen, ash, sucrose, xylan, cellulose, lignin and starch based on data from the first harvest of the 2010 China multi-cut study

	Yield			Tissue nitrogen		Ash	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	17	50.355652	<.0001	7.7755196	0.0013	596.24176	<.0001
N-rate	4	52.4727034	<.0001	19.71058333	<.0001	231.50642	0.0004
Variety	2	206.7696565	<.0001	8.77716667	0.038	3714.651465	<.0001
Rep	3	44.5422737	0.0002	5.4055	0.1047	498.426547	<.0001
N-rate*var	8	12.3736414	0.0433	2.44633333	0.4605	35.687703	0.451
Error	42	5.525305		2.4810952		35.7199	
Total	59						

	Sucrose			Xylan		Cellulose	
Source	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	17	6720.441	<.0001	445.729593	<.0001	2604.65372	<.0001
N-rate	4	2534.39592	<.0001	32.554009	0.4718	192.89915	0.6472
Variety	2	42743.07369	<.0001	3377.097229	<.0001	17580.23996	<.0001
Rep	3	5160.78644	<.0001	180.694153	0.0047	2468.16896	0.0002
N-rate*var	8	392.67588	0.3292	18.863765	0.8329	117.81622	0.9243
Error	42	330.5451		36.115647		308.55914	
Total	59						

Source	Lignin			Starch
	df	Mean square	Pr>F	Mean square
Model	17	2900.44352	<.0001	6763.9064
N-rate	4	228.10749	0.0005	831.8886
Variety	2	16920.5191	<.0001	52678.2648
Rep	3	4738.3217	<.0001	1717.964
N-rate*var	8	42.38832	0.3514	143.5541
Error	42	36.85773		390.298
Total	59			

Table A8. Analysis of variance for dependent variables, yield, tissue nitrogen, ash, sucrose, xylan, cellulose, lignin and starch based on data from the 2010 China single-cut study

Source	Yield			Tissue nitrogen		Ash	
	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	26	66.699234	<.0001	5.117945	<.0001	81.922093	<.0001
N-rate	7	16.397418	0.1492	12.00189985	<.0001	46.544746	0.0508
Variety	2	689.953825	<.0001	9.16400729	0.0032	742.638907	<.0001
Rep	3	8.882327	0.4618	3.75903993	0.062	21.467653	0.4046
N-rate*var	14	15.203109	0.1398	1.38915253	0.5161	18.177172	0.6297
Error	69	10.229707		1.4686689		21.771348	
Total	95						

Source	Sucrose			Xylan		Cellulose	
	df	Mean square	Pr>F	Mean square	Pr>F	Mean square	Pr>F
Model	26	1475.60242	<.0001	180.635363	<.0001	1048.16033	<.0001
N-rate	7	1212.32527	0.001	84.780306	0.0683	437.65856	0.2117
Variety	2	13544.68902	<.0001	1729.160142	<.0001	9030.75497	<.0001
Rep	3	237.80707	0.505	92.004003	0.1002	922.63207	0.0368
N-rate*var	14	148.32762	0.9304	26.3375	0.84	239.93946	0.6886
Error	69	302.00903		42.524576		308.36547	
Total	95						

Source	Lignin			Starch
	df	Mean square	Pr>F	Mean square
Model	26	323.23295	0.0002	2005.28911
N-rate	7	398.350316	0.0022	1051.77759
Variety	2	1814.767554	<.0001	17917.67968
Rep	3	282.395053	0.0616	136.19093
N-rate*var	14	81.348866	0.7282	609.36725
Error	69	110.06325		578.03946
Total	95			

APPENDIX B

Comparison of means

Table B1. Comparison of the means of sorghum biomass yield by variety and N-rate for the 2008 College Station harvest (Mg ha^{-1})

N-rate (kg N/ha)	Variety					
	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	14.74	14.42	17.04	15.95	15.58	13.74
34	16.24	19.76	14.85	20.92	14.61	17.18
78	15.10	20.04	16.33	14.80	19.06	16.82
123	14.53	21.56	15.41	16.67	15.48	17.72
168	11.83	17.01	16.69	17.90	16.84	18.27

$LSD_{0.05}$ =4.97

Table B2. Comparison of the means of tissue nitrogen concentration in sorghum biomass by variety and N-rate for the 2008 College Station harvest (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	8.78	6.55	5.68	5.88	7.45	8.45
34	9.20	5.25	7.88	6.73	7.78	8.40
78	8.18	7.13	8.50	7.48	7.25	8.93
123	8.28	7.98	8.58	6.48	7.90	8.30
168	8.95	8.28	9.38	7.23	8.13	8.90

$LSD_{0.05}$=2.24

Table B3. Comparison of the means of tissue ash concentration in sorghum biomass by variety and N-rate for the 2008 College Station harvest (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	57.25	55.94	52.83	54.09	64.19	62.70
34	64.09	53.23	59.57	51.17	62.63	66.02
78	57.74	56.42	59.21	57.07	61.73	67.63
123	59.31	56.40	60.17	57.64	61.79	69.76
168	57.28	56.82	60.87	52.52	65.49	68.24

$LSD_{0.05}$=7.35

Table B4. Comparison of the means of sucrose concentration in sorghum biomass by variety and N-rate for the 2008 College Station harvest (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	118.24	114.65	141.74	155.56	106.48	114.40
34	128.01	116.07	123.01	137.81	115.75	74.95
78	129.39	110.09	129.01	148.75	104.65	73.06
123	124.01	105.57	125.96	142.87	108.45	81.21
168	118.34	96.39	115.60	127.94	124.07	78.38

$LSD_{0.05}$=23.65

Table B5. Comparison of the means of tissue xylan concentration in sorghum biomass by variety and N-rate for the 2008 College Station harvest (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	141.09	148.44	140.44	142.20	149.44	146.12
34	140.24	149.79	139.76	140.59	147.14	154.47
78	139.06	149.47	139.77	140.14	147.81	153.27
123	141.36	150.48	140.76	143.88	148.62	156.63
168	142.18	150.50	141.36	141.79	146.76	153.88

$LSD_{0.05}$=4.19

Table B6. Comparison of the means of cellulose concentration in sorghum biomass by variety and N-rate for the 2008 College Station harvest (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	224.57	242.23	229.79	238.77	244.16	237.57
34	227.75	243.35	225.85	229.02	239.31	249.66
78	222.52	241.68	226.84	234.12	238.67	246.09
123	227.31	244.98	230.14	238.35	241.42	256.83
168	226.21	243.64	228.81	229.37	242.30	249.62

$LSD_{0.05}$=8.88

Table B7. Comparison of the means of lignin concentration in sorghum biomass by variety and N-rate for the 2008 College Station harvest (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	101.71	108.00	85.15	92.37	99.43	97.39
34	94.68	108.75	88.14	99.48	99.81	119.70
78	98.39	109.14	88.24	95.06	100.38	117.06
123	97.50	111.37	87.18	97.16	102.62	117.24
168	99.92	111.86	90.85	101.21	94.72	116.12

$LSD_{0.05}$= 6.77

Table B8. Comparison of the means of starch concentration in sorghum biomass by variety and N-rate for the 2008 College Station harvest (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	164.72	101.78	169.20	153.64	120.93	141.33
34	188.32	92.03	164.85	163.79	126.71	55.05
78	182.52	92.51	164.03	156.00	129.28	64.90
123	178.23	78.36	157.89	135.37	121.78	53.88
168	167.49	80.98	151.39	155.52	133.26	59.22

$LSD_{0.05}$=30.00

2009 College Station first cut

Table B9. Comparison of the means of sorghum biomass yield by variety and N-rate for the first harvest of 2009 College Station (Mg ha^{-1})

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	6.18	10.28	9.54	11.00	9.39	11.44
42	8.76	12.76	10.24	12.60	10.47	10.41
84	8.42	11.89	9.49	12.79	12.04	12.59
126	9.94	13.28	10.60	10.66	10.56	12.00
168	8.12	11.16	8.27	9.55	12.03	11.39

$LSD_{0.05}$=3.34

Table B10. Comparison of the means of tissue nitrogen concentration in sorghum biomass by variety and N-rate for the first harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	6.35	7.68	6.58	4.85	6.46	6.95
42	6.30	8.25	7.33	8.98	8.73	8.18
84	8.85	7.98	9.50	10.40	9.63	8.50
126	10.38	10.88	9.60	8.28	10.60	11.60
168	9.65	13.50	9.15	11.30	11.35	13.90

$LSD_{0.05}$=3.22

Table B11. Comparison of the means of ash concentration in sorghum biomass by variety and N-rate for the first harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	54.98	57.58	55.16	54.73	61.01	65.27
42	54.79	60.43	59.82	62.59	67.59	66.35
84	61.00	60.01	60.19	64.67	72.69	68.71
126	65.48	65.90	62.76	65.34	72.94	74.41
168	61.32	70.48	63.62	65.88	74.64	83.19

$LSD_{0.05}$= 8.41

Table B12. Comparison of the means of sucrose concentration in sorghum biomass by variety and N-rate for the first harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	156.73	141.03	157.06	167.91	140.26	115.69
42	158.06	149.23	151.00	150.53	112.93	103.78
84	146.53	130.29	142.57	154.72	107.54	100.89
126	133.64	126.82	141.79	144.41	110.37	95.68
168	154.04	104.83	138.74	137.47	99.53	94.23

$LSD_{0.05}$= 24.20

Table B13. Comparison of the means of xylan concentration in sorghum biomass by variety and N-rate for the first harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	143.91	151.25	139.41	140.97	147.15	157.03
42	143.01	147.08	140.99	140.41	146.16	159.36
84	142.49	152.69	140.56	140.13	146.04	160.97
126	142.51	151.06	140.56	144.41	149.72	157.56
168	141.91	153.75	141.62	144.53	150.40	154.95

$LSD_{0.05}$=5.51

Table B14. Comparison of the means of cellulose concentration in sorghum biomass by variety and N-rate for the first harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	237.3263	253.7438	231.2313	234.105	243.5538	264.985
42	235.9675	246.805	234.9275	230.4975	235.94	267.82
84	233.935	256.3963	231.8063	232.5938	236.4925	271.35
126	232.795	254.6488	232.395	239.6488	247.1388	263.735
168	234.6313	257.3638	234.38	239.5775	246.1575	260.03

$LSD_{0.05}$=10.95

Table B15. Comparison of the means of lignin concentration in sorghum biomass by variety and N-rate for the first harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	76.74	81.75	66.09	73.00	79.54	94.29
42	82.07	82.72	66.02	75.37	80.59	102.08
84	81.15	90.47	68.56	75.79	81.62	104.67
126	75.71	90.00	66.87	78.64	85.05	104.08
168	77.71	100.48	70.91	85.01	86.94	99.48

$LSD_{0.05}$= 8.54

Table B16. Comparison of the means of starch concentration in sorghum biomass by variety and N-rate for the first harvest of 2009 College Station (g kg^{-1} dry matter)

Starch

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	211.1013	139.1025	230.0863	225.1788	199.885	90.43375
42	194.9238	161.3413	240.1463	222.1388	222.7075	72.22625
84	195.0925	111.2013	229.785	209.1575	215.8063	71.7125
126	223.1313	107.4938	227.6825	191.2538	164.73	62.6825
168	196.405	78.5925	205.2113	175.965	160.5913	66.25875

$LSD_{0.05}$=44.48

2009 College Station second cut

Table B17. Comparison of the means sorghum of biomass yield by variety and N-rate for the second harvest of 2009 College Station (Mg ha^{-1})

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	2.01	3.95	2.44	3.45	4.57	2.02
42	3.57	5.04	2.60	4.58	4.27	4.22
84	3.46	6.50	3.63	6.48	5.22	6.08
126	3.80	4.22	3.72	4.10	6.22	5.44
168	3.18	4.33	3.00	5.22	7.16	4.88

$LSD_{0.05}$=1.94

Table B18. Comparison of the means of tissue nitrogen concentration in sorghum biomass by variety and N-rate for the second harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	9.00	8.13	10.40	9.40	9.08	9.93
42	8.30	7.60	7.88	7.25	9.35	9.23
84	8.85	6.98	8.80	8.25	9.15	8.45
126	10.43	8.38	9.13	8.60	10.63	8.88
168	11.35	9.13	9.83	9.53	10.55	10.38

$LSD_{0.05}$=1.53

Table B19. Comparison of the means of ash concentration in sorghum biomass by variety and N-rate for the second harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	64.68	59.44	66.07	64.65	69.90	67.00
42	57.48	61.19	60.62	61.10	71.81	68.16
84	60.53	61.34	62.50	65.95	70.02	68.68
126	65.49	62.74	61.88	67.65	74.71	68.72
168	65.69	62.11	65.72	65.54	78.49	70.43

$LSD_{0.05}$=3.90

Table B20. Comparison of the means of sucrose concentration in sorghum biomass by variety and N-rate for the second harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	139.61	138.08	123.74	143.26	112.29	116.41
42	151.94	138.57	132.10	146.93	89.33	118.99
84	144.78	142.09	124.34	138.34	92.62	122.67
126	137.51	141.62	132.24	134.97	87.22	122.85
168	135.85	140.39	120.88	146.82	91.46	120.15

$LSD_{0.05}$=13.99

Table B21. Comparison of the means of xylan concentration in sorghum biomass by variety and N-rate for the second harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	145.7875	151.55	145.3188	144.4113	147.7488	152.8325
42	145.7575	150.1363	148.6488	148.3225	152.3138	154.0875
84	145.7088	151.41	150.9738	145.5975	155.0125	153.2425
126	146.1063	150.7625	150.6888	147.4663	152.82	153.3463
168	146.1613	147.0775	152.2288	144.6938	150.49	152.5838

$LSD_{0.05}$=4.41

Table B22. Comparison of the means of cellulose concentration in sorghum biomass by variety and N-rate for the second harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	244.165	255.2875	246.6188	241.215	243.1675	255.785
42	242.7138	254.145	253.6513	250.9425	247.4913	259.1025
84	242.7325	255.0238	255.2388	241.4138	255.6263	257.6475
126	243.3613	254.45	254.7288	246.9175	250.82	257.4475
168	241.8425	244.3013	255.9725	243.1313	248.1388	255.9375

$LSD_{0.05}$=9.32

Table B23. Comparison of the means of lignin concentration in sorghum biomass by variety and N-rate for the second harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	89.72625	86.64375	80.44875	84.5175	89.5175	90.875
42	86.405	87.1425	77.6375	82.94625	88.51375	89.87875
84	85.31875	89.6525	78.29375	82.185	91.34625	89.73
126	87.83375	89.095	83.32125	84.03	93.1225	87.76125
168	85.2275	88.895	83.5575	84.2325	92.3825	90.16375

$LSD_{0.05}$=5.04

Table B24. Comparison of the means of starch concentration in sorghum biomass by variety and N-rate for the second harvest of 2009 College Station (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	M 81E	Millenium BMR	Rio	Silmaker 6500	Sugragraze Ultra
0	162.8225	120.98	149.5	172.7113	182.1863	119.0213
42	167.535	128.6663	140.6438	160.3263	183.3513	108.615
84	174.7838	124.7688	142.3538	201.9938	155.3913	116.3938
126	163.225	125.9925	120.8488	176.6113	159.0263	123.4663
168	165.4863	159.4875	122.215	188.9338	161.6113	123.97

$LSD_{0.05}$=43.85

2010 College Station multicut first cut

Table B25. Comparison of the means of sorghum biomass yield by variety and N-rate for the first harvest of the 2010 College Station multicut study (Mg ha^{-1})

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	15.4607	14.92333	16.62145
34	15.67977	15.77614	16.22949
78	14.69652	14.48774	20.58749
123	13.85268	15.89856	22.30248
168	15.59141	14.4313	24.54697
224			21.60511

$LSD_{0.05}$=4.38

Table B26. Comparison of the means of tissue nitrogen concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	8.775	8.8	9.15
34	7.425	8.4	8.35
78	8.225	8.775	9.475
123	8.7	8.8	8.8
168	8.6	9.875	8.075
224			9.775

$LSD_{0.05}$=2.26

Table B27. Comparison of the means of ash concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	43.45625	45.29375	60.86375
34	38.355	40.06125	61.755
78	42.1925	43.90625	63.105
123	42.765	43.0025	59.81625
168	45.36875	53.20625	59.8325
224			60.14125

$LSD_{0.05}$=9.52

Table B28. Comparison of the means of sucrose concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	128.135	139.4388	82.04875
34	153.41	148.0775	56.945
78	148.6775	131.135	65.56375
123	133.6788	147.0688	65.1225
168	126.2888	121.4038	65.88
224			70.84875

$LSD_{0.05}$=21.53

Table B29. Comparison of the means of xylan concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	140.83	139.8175	157.0988
34	135.2488	137.7413	166.425
78	136.7825	143.035	165.2938
123	140.46	139.3938	167.9175
168	146.6825	144.295	168.8838
224			165.5475

$LSD_{0.05}$=8.29

Table B30. Comparison of the means of cellulose concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	213.0975	217.4913	259.43
34	202.0875	211.2275	281.69
78	203.8138	226.5275	279.6738
123	212.24	217.0188	287.2363
168	232.2338	229.8913	287.9988
224			281.445

$LSD_{0.05}$=23.05

Table B31. Comparison of the means of lignin concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	101.5888	85.2825	122.2538
34	96.96125	88.445	141.635
78	102.275	86.99875	132.42
123	106.0513	87.2425	139.7663
168	106.32	84.08125	137.9375
224			136.4113

$LSD_{0.05}$=13.59

Table B32. Comparison of the means of starch concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	175.5288	152.2475	92.55625
34	195.53	169.0763	65.6175
78	176.5038	140.0813	71.64875
123	168.8725	153.0175	69.36
168	139.5788	132.6788	66.0825
224			64.615

$LSD_{0.05}$=23.50

2010 College Station multicut second cut

Table B33. Comparison of the means of sorghum biomass yield by variety and N-rate for the second harvest of the 2010 College Station multicut study (Mg ha^{-1})

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	5.80	5.48	5.88
22	4.59	6.35	6.03
52	5.24	2.49	5.77
82	4.85	4.63	3.75
112	6.26	4.01	5.37

$LSD_{0.05}$=1.95

Table B34. Comparison of the means of tissue nitrogen concentration in sorghum biomass by variety and N-rate for the second harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	9.15	10.725	10.65
22	9.95	11.25	11.325
52	10.5	12.32	11.325
82	11.025	12.925	13.9
112	11.75	13.9	13.275

$LSD_{0.05}$=2.17

Table B35. Comparison of the means of ash concentration in sorghum biomass by variety and N-rate for the second harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	57.98	63.52	70.00
22	62.17	65.39	73.97
52	61.03	65.13	69.97
82	61.78	69.40	74.68
112	65.94	70.18	76.96

$LSD_{0.05}$=7.16

Table B36. Comparison of the means of sucrose concentration in sorghum biomass by variety and N-rate for the second harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	146.03	109.92	87.95
22	140.29	109.56	96.05
52	140.59	121.76	101.49
82	139.84	90.73	88.96
112	126.05	102.14	95.99

$LSD_{0.05}$=22.19

Table B37. Comparison of the means of xylan concentration in sorghum biomass by variety and N-rate for the second harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	142.82	156.67	165.12
22	144.53	152.92	160.06
52	143.35	148.89	159.18
82	144.46	161.58	160.05
112	146.99	153.06	156.25

$LSD_{0.05}$=9.06

Table B38. Comparison of the means of cellulose concentration in sorghum biomass by variety and N-rate for the second harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	233.80	275.08	282.59
22	239.43	266.22	271.54
52	232.83	253.23	269.38
82	236.94	284.57	270.78
112	244.25	260.00	262.66

$LSD_{0.05}$=24.02

Table B39. Comparison of the means of lignin concentration in sorghum biomass by variety and N-rate for the second harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	74.21	65.32	93.54
22	76.18	72.45	87.16
52	75.33	63.08	89.90
82	79.15	79.87	90.79
112	84.79	73.29	90.76

$LSD_{0.05}$=15.80

Table B40. Comparison of the means of starch concentration in sorghum biomass by variety and N-rate for the second harvest of the 2010 College Station multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Della	Millenium BMR	Sugragraze Ultra
0	182.46	113.10	95.73
22	170.62	119.41	102.96
52	176.53	130.92	110.15
82	166.50	87.86	95.55
112	156.42	112.45	101.03

$LSD_{0.05}$=34.15

2010 College Station single-cut

Table B41. Comparison of the means of sorghum biomass yield by variety and N-rate for the 2010 College Station single-cut study (Mg ha^{-1})

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	15.17	10.98	15.97
39	15.30	11.53	20.76
78	19.36	13.64	15.49
118	15.63	12.11	11.41
157	24.71	11.77	19.72
196	13.72	10.81	16.63
235	10.72	14.84	12.31
275	24.88	12.06	20.67

$LSD_{0.05}$=5.24

Table B42. Comparison of the means of tissue nitrogen concentration in sorghum biomass by variety and N-rate for the 2010 College Station single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	5.36	6.16	8.72
39	6.07	6.18	9.26
78	6.92	6.93	9.24
118	6.91	7.11	9.74
157	7.90	8.39	9.99
196	7.98	8.46	9.82
235	8.01	7.51	10.49
275	7.95	8.23	11.68

$LSD_{0.05}$=1.32

Table B43. Comparison of the means of ash concentration in sorghum biomass by variety and N-rate for the 2010 College Station single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	48.30	54.26	65.14
39	48.60	55.78	67.83
78	51.98	56.13	66.82
118	52.10	59.69	65.34
157	54.27	59.24	68.67
196	55.09	62.17	70.55
235	55.16	60.22	68.73
275	53.51	59.72	71.54

$LSD_{0.05}$=5.71

Table B44. Comparison of the means of sucrose concentration in sorghum biomass by variety and N-rate for the 2010 College Station single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	165.25	149.72	97.98
39	168.48	143.76	90.71
78	148.82	150.23	87.67
118	157.37	124.75	93.06
157	136.03	127.97	84.07
196	137.42	119.19	80.58
235	135.65	140.31	85.07
275	146.63	130.35	70.12

$LSD_{0.05}$=21.03

Table B45. Comparison of the means of xylan concentration in sorghum biomass by variety and N-rate for the 2010 College Station single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	158.01	151.78	170.22
39	153.97	152.80	170.43
78	159.41	152.39	174.63
118	157.03	160.62	170.92
157	162.37	159.75	171.37
196	162.67	161.01	175.75
235	162.86	152.76	169.71
275	161.80	157.54	176.24

$LSD_{0.05}$=7.83

Table B46. Comparison of the means of cellulose concentration in sorghum biomass by variety and N-rate for the 2010 College Station single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	276.36	254.65	293.02
39	266.51	257.10	294.24
78	275.90	258.38	307.89
118	267.85	279.28	296.26
157	279.84	276.61	293.23
196	282.19	280.12	307.19
235	282.02	260.77	287.24
275	281.24	270.31	302.12

$LSD_{0.05}$=21.85

Table B47. Comparison of the means of lignin concentration in sorghum biomass by variety and N-rate for the 2010 College Station single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	82.74	67.66	94.42
39	76.89	73.69	99.26
78	78.32	71.30	104.56
118	81.58	99.05	99.96
157	89.85	83.68	99.46
196	86.98	89.26	104.41
235	87.92	73.43	99.71
275	85.53	85.56	110.01

$LSD_{0.05}$=15.42

Table B48. Comparison of the means of starch concentration in sorghum biomass by variety and N-rate for the 2010 College Station single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	131.51	187.11	109.82
39	145.00	183.21	101.22
78	138.17	176.21	84.81
118	137.71	133.12	98.62
157	120.70	144.16	100.18
196	121.74	135.82	77.55
235	121.85	164.66	109.41
275	120.50	151.44	84.04

$LSD_{0.05}$=36.45

2010 China multicut first cut

Table B49. Comparison of the means of sorghum biomass yield by variety and N-rate for the first harvest of the 2010 China multicut study (Mg ha^{-1})

N-rate (kg N/ha)	Exp. variety	Millenium BMR	Sugragraze Ultra
0	9.72	8.05	10.82
34	9.79	11.44	14.91
78	10.88	11.07	19.36
123	11.52	14.02	17.89
168	11.84	11.54	19.73

$LSD_{0.05}$=3.35

Table B50. Comparison of the means of tissue nitrogen concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 China multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Exp. variety	Millenium BMR	Sugragraze Ultra
0	8.03	7.33	8.33
34	5.78	6.85	8.63
78	7.98	7.35	8.25
123	7.63	9.15	8.28
168	9.43	10.18	11.83

$LSD_{0.05}$=1.71

Table B51. Comparison of the means of ash concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 China multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Exp. variety	Millenium BMR	Sugragraze Ultra
0	50.66875	45.7625	73.34875
34	40.5675	46.58125	68.7225
78	49.48	43.815	70.4425
123	49.09125	53.7775	71.26875
168	54.6875	56.605	79.7475

$LSD_{0.05}$=8.53

Table B52. Comparison of the means of sucrose concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 China multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Exp. variety	Millenium BMR	Sugragraze Ultra
0	103.06	133.44	32.44
34	145.20	140.33	50.16
78	116.07	135.66	40.49
123	111.73	119.95	45.42
168	91.33	94.02	29.48

$LSD_{0.05}$=25.94

Table B53. Comparison of the means of xylan concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 China multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Exp. variety	Millenium BMR	Sugragraze Ultra
0	154.61	152.13	177.13
34	148.90	149.76	172.39
78	152.04	148.84	176.14
123	153.33	149.53	174.47
168	155.72	154.30	171.66

$LSD_{0.05}$=8.58

Table B54. Comparison of the means of cellulose concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 China multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Exp. variety	Millenium BMR	Sugragraze Ultra
0	253.10	263.08	311.63
34	248.61	252.58	299.53
78	247.37	246.16	305.69
123	250.20	245.63	304.58
168	253.97	257.31	294.14

$LSD_{0.05}$=25.07

Table B55. Comparison of the means of lignin concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 China multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Exp. variety	Millenium BMR	Sugragraze Ultra
0	110.57	80.09	141.48
34	102.63	78.35	135.80
78	106.25	83.06	146.39
123	107.69	87.74	144.45
168	116.36	92.93	143.64

$LSD_{0.05}$=8.66

Table B56. Comparison of the means of starch concentration in sorghum biomass by variety and N-rate for the first harvest of the 2010 China multicut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	Exp. variety	Millenium BMR	Sugragraze Ultra
0	142.43	123.25	41.34
34	155.94	131.96	59.01
78	147.39	140.81	47.45
123	135.10	132.77	45.06
168	124.03	117.91	41.34

$LSD_{0.05}$=28.19

2010 China single-cut

Table B57. Comparison of the means of sorghum biomass yield by variety and N-rate for the 2010 China single-cut study (Mg ha^{-1})

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	21.56	9.79	11.15
39	15.33	11.20	9.23
78	22.29	12.63	10.33
118	21.43	8.50	10.21
157	18.64	9.10	9.21
196	17.70	11.89	12.05
235	15.74	9.91	9.70
275	16.40	12.05	12.53

$LSD_{0.05}$=4.51

Table B58. Comparison of the means of tissue nitrogen concentration in sorghum biomass by variety and N-rate for the 2010 China single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	5.65	5.90	7.74
39	7.11	7.58	7.03
78	5.70	7.20	7.89
118	6.71	7.07	7.22
157	6.43	7.91	7.67
196	8.73	8.45	8.57
235	7.60	8.13	8.88
275	9.05	8.69	10.52

$LSD_{0.05}$=1.71

Table B59. Comparison of the means of ash concentration in sorghum biomass by variety and N-rate for the 2010 China single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	49.26	56.08	61.03
39	53.98	60.06	56.15
78	48.36	60.01	59.99
118	51.32	58.81	58.92
157	51.07	60.78	59.35
196	55.14	63.49	60.33
235	54.19	59.35	61.71
275	53.16	64.47	65.94

$LSD_{0.05}$=6.58

Table B60. Comparison of the means of sucrose concentration in sorghum biomass by variety and N-rate for the 2010 China single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	144.43	133.97	93.64
39	121.14	126.69	98.54
78	135.36	122.29	84.10
118	131.23	122.35	94.99
157	127.10	116.32	79.85
196	105.55	107.59	78.11
235	110.02	112.19	84.96
275	113.90	103.21	69.99

$LSD_{0.05}$=24.51

Table B61. Comparison of the means of xylan concentration in sorghum biomass by variety and N-rate for the 2010 China single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	162.51	163.36	177.57
39	171.18	166.55	176.73
78	165.16	166.49	181.92
118	164.76	168.40	179.34
157	166.64	167.16	184.95
196	172.26	170.97	185.26
235	173.86	169.92	181.66
275	169.13	172.23	179.72

$LSD_{0.05}$=9.20

Table B62. Comparison of the means of cellulose concentration in sorghum biomass by variety and N-rate for the 2010 China single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	274.43	274.58	306.03
39	292.88	280.69	304.65
78	276.74	279.30	319.24
118	275.57	287.64	308.93
157	280.14	281.98	324.79
196	292.44	289.26	326.31
235	302.26	289.92	316.68
275	282.59	294.36	303.55

$LSD_{0.05}$=24.77

Table B63. Comparison of the means of lignin concentration in sorghum biomass by variety and N-rate for the 2010 China single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	90.65	88.15	110.83
39	101.33	98.51	104.80
78	92.56	99.25	118.20
118	96.89	98.31	106.24
157	93.36	100.55	115.20
196	111.99	109.74	116.54
235	107.74	103.91	117.08
275	106.49	108.45	119.25

$LSD_{0.05}$=14.80

Table B64. Comparison of the means of starch concentration in sorghum biomass by variety and N-rate for the 2010 China single-cut study (g kg^{-1} dry matter)

N-rate (kg N/ha)	M 81E	Rio	Silmaker 6500
0	151.39	142.87	92.08
39	120.63	127.09	112.48
78	158.39	126.02	77.88
118	151.76	128.75	97.60
157	150.79	130.16	91.34
196	121.38	112.21	82.29
235	110.85	122.79	79.76
275	128.06	111.24	95.73

$LSD_{0.05}$=33.92

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