DIRECT COMPARISON OF BIOMASS YIELDS OF ANNUAL AND PERENNIAL BIOFUEL CROPS

by

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B.S., Kansas State University, 2007

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2009

Approved by:

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Abstract

Volatile energy prices, energy independency, and environmental concerns have increased the demand for renewable fuel production in the United States. The current renewable fuel industry in the United States has developed around the conversion of starch into ethanol fuel, supplied mainly by corn (*Zea mays* L.) grain. Future energy demands cannot be met by corn grain alone; therefore greater amounts of biomass from traditional and alternative crops must be utilized. Nutrient removal by selected biofuel crops is important in order to determine biomass quality, required fertilizer inputs, and economic viability of biofuel cropping systems. The objectives of this study were to evaluate grain, stover, total biomass, and estimated ethanol yields of annual and perennial C4 crops grown under the same soil and weather conditions; and fermentable carbohydrate (FC) yields from extracted sweet sorghum juice. In addition, nitrogen (N), phosphorus (P) and potassium (K) concentrations of biomass were evaluated to determine total nutrient removal for annual and perennial crops. Field trials, at two locations in northeast Kansas, included corn, sorghum [*Sorghum bicolor* (L.) Moench] and perennial warm-season grass cultivars. Yields and nutrient removal were greater for annual crops than perennial grasses. Annual crop yields varied among cultivars, but were similar between locations and years. Perennial grass yields improved significantly from the 2007 establishment year to 2008, however nutrient removal was not affected by the yield increase. The highest grain yield and grain nutrient removal amounts were observed for corn across both years and locations. Total biomass yields were greatest for sweet and photoperiod sensitive sorghum cultivars. Average extracted sweet sorghum FC yields were 4.8 Mg ha^{-1}. Estimated ethanol yields of sweet sorghum were greater than all other crop cultivars. Overall, nutrient removal was most affected by biomass yield variation among crop cultivars; however P concentrations, and subsequent removal, were dependent upon soil P levels at individual locations. These results suggest that annual crops can achieve the greatest biomass yields for multiple renewable fuel conversion processes, but are associated with high nutrient removal levels which must be considered when evaluating biofuel energy cropping systems.

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Acknowledgements

I would like to thank my major professor, Dr. Scott Staggenborg for his guidance and confidence in me to take on this project, which undoubtedly allowed me to gain a great amount experience and knowledge. I would also like to thank my committee members, Dr. Vara Prasad and Dr. Donghai Wang, for their guidance and support. Special thanks to ICM of Colwich, KS for their project contributions and funding.

A great deal of gratitude goes to Vernon Schaffer and the Agronomy North Farm staff for all of their time, assistance, and resources utilized to make this project happen. I also owe the KSU Weed Science Department, Crop Performance Testing, and Soil Testing Lab staff much gratitude for their guidance, time, and resource contributions throughout the project's duration. I would also like to thank George and John Rush, along with Lawrence Blanton, Jr. and Bill Foster, for their generosity, cooperation, and donation of time and machinery to assist at the Troy, KS field site.

I am also grateful to Kevin Swenson, Lucas Haag, Kyle Shroyer, Scott Dooley, and Yared Assefa for the countless hours of help they committed to this project. Much appreciation goes to our student workers; Jeremy Olson, Josh Carlin, Kelly Yunghans, Emily Bunck, Collin Duncan, Michael Straily, Nicole Rezac, and David Shroyer for all of their assistance .

Last, but certainly not least, I would like to thank my closest friends and family members for their endless support and encouragement throughout the duration of this project which pushed me through the most difficult times. I cannot begin to imagine the completion of this project without the generous support of everyone mentioned.

CHAPTER 1 - Literature Review

Annual Crop Yields

In recent years, increased fuel prices, requirements for reduced greenhouse gas emissions and a push towards decreasing the reliance on foreign oil has stimulated a rapid increase in ethanol production from energy-based crops within the United States. The U.S. Energy Independence and Security Act of 2007 requires the annual production of 135 billion liters (L) of renewable fuel by 2022, of which 79 billion L must be from cellulosic or other advanced conversion processes (Sissine, 2007). The current ethanol industry in Kansas, and the United States, is designed around the fermentation of corn (*Zea mays.* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench] grain. In 2008, there were 12 operating ethanol plants in Kansas with a combined ethanol production capacity of 1.7 billion L annually (O'Brien et al., 2008). This level of ethanol production requires 29% of the total corn and sorghum grain produced annually in Kansas (O'Brien et al., 2008). The state's livestock industry, which has relied upon this feedstock production, is impacted by the decrease in available grain. Lignocellulosic (LC) biomass (the non-grain or root portion of a crop) and fermentable carbohydrates (FC) from current production, or alternative, bioenergy crops are viable sources for ethanol production, gasification, and combustion processes for heat or electricity generation which can assist renewable fuel demands and decrease the reliance on current grain crops.

In general, crops with a four-carbon (C4) photosynthetic pathways produce 30% more dry matter (DM) per unit of water than three-carbon (C3) crops and are more adapted to semi-arid production regions where moisture supply is the limiting production factor (Samson and Knopf, 1994). The C4 physiology has made annual and perennial grass crops the main focus for alcohol based biofuels, as well as other forms of bioenergy conversion requiring the use of biomass. Select annual and perennial C4 crops of focus include corn, sorghum, sugar cane (*Saccharum officinarum*), and warm season (WS) grasses.

Corn is a widely adaptable C4 annual crop used in many cropping systems across KS, and throughout the United States, for grain and forage production. Corn grain (starch) currently makes up about 95% of the total feedstock grain used for ethanol production in the United States (Renewable Fuels Association, 2007). Due to its production in diverse environments, corn grain yields can vary significantly across regions. In Kansas, average dryland corn grain yields range from 1.7 Mg ha^{-1} in the lower rainfall northwest region to 7.0 Mg ha^{-1} in the higher rainfall northeast region. Irrigated corn grain yields average 11.5 Mg ha^{-1} across the state (Roozeboom et al., 2007). The harvest index (the percentage of grain DM relative to total aboveground plant DM) for corn ranges from 45 – 50%. Nielsen (1995) stated that corn grain yields make up 45% of the aboveground biomass, therefore dry grain yields of 6.3 to 9.4 Mg ha^{-1} would correspond to dry stover yields of 6.7 to 10.1 Mg ha^{-1}. Pordesimo et al. (2004) found that corn total DM yields were greatest at the time of grain physiological maturity, and declined after this stage due to weathering of leaf blades, tassels, tops of stalks and husks. The study reported grain and dry stover yields to be 13.0 Mg ha^{-1} and 15.6 Mg ha^{-1}, respectively, with a grain harvest index of 46%. Based upon these harvest indices, the stover DM yields (LC biomass) of corn can be equal to, or greater than, grain DM yields. Based on average the U.S. corn grain yield, annual combined grain and stover biomass could exceed 570 million Mg (National Agricultural Statistics Service, 2009).

Research has shown that corn can produce 1.0 to 3.0 Mg ha^{-1} higher grain yields when grown following soybean [*Glycine max.* (L.) Merr.] than when grown in a continuous corn (CC) monoculture (Baldock et al., 1981; Hicks and Peterson, 1982; Peterson and Varvel, 1989; West et al., 1996). Improved yield of corn rotated with soybean is most commonly attributed to the biological fixation of nitrogen (N) by soybean. In southeast Nebraska (NE), Wilhelm and Wortmann (2004) reported long term (16 years) grain yields of CC and corn rotated annually with soybean to be 5.83 and 7.10 Mg ha^{-1}, respectively. Maloney et al. (1999) observed corn grain and silage yields to be greater following both nodulated and non-nodulated soybean than CC, suggesting the improved rotated corn yield is not due to the N fixation effect of the soybean. Results showed CC with 180 kg N ha^{-1} did not yield differently than corn following soybean, with either nodulation characteristic, with 90 kg N ha^{-1}. Increased corn yields from the rotation effect of soybean is likely due to several factors, including; reduced insect and disease pressure, rate of residue breakdown and N immobilization, and changes in soil texture and/or structure increasing water infiltration (Blackmer and Green, 1995; Boosalis and Doupnik, 1976; Karlen et al., 1994). Select cropping system management will optimize yields of corn for biomass production across many different dryland and irrigated environments.

Sorghum is a drought-tolerant C4 grass crop species with high starch, fermentable carbohydrate (FC), and LC production capabilities. Sorghums can be classified into four main groups depending on their main production characteristics: grain sorghum, forage sorghum (FS), high-tonnage (energy), and sweet sorghum. While starches from sorghum grain and FC from sweet sorghum can be used for ethanol conversion, all sorghum groups produce LC biomass for ethanol and other energy conversion processes. In the United States, it is estimated that annual combined sorghum production uses seven million hectares of farmland (Rooney et al., 2007). Currently, sorghum grain makes up 4% of the total grain used for ethanol production in the U.S. (Renewable Fuels Association, 2007). Sorghum has great potential as a biofuel crop due to its high carbohydrate content in the vegetative and grain components of the plant, depending upon cultivar selection (Miller and Creelman, 1980).

Sorghum is generally considered to have higher water use efficiency (WUE) than that of corn, thus sorghum is well adapted to semiarid environments (Martin et al., 1976). Sorghum is capable of DM accumulation in stover even if grain production is reduced from water stress at critical reproductive growth stages due to its ability to continue vegetative production after a drought-induced dormancy (Fribourg, 1995; Unger and Weise, 1979). McCollum et al. (2005) reported WUE, defined as Mg DM/ha-cm of irrigation water, of corn, FS, brown mid-rib (*bmr*) FS, and photoperiod sensitive (PS) sorghums to be 1.0, 1.7, 1.5 and 2.2 Mg/ha-cm, respectively. Unger (1988) found that FS is more water use efficient than grain sorghum based on total DM production, which is explained by sorghum's water requirements being less critical at vegetative growth stages compared with reproductive stages.

Forage sorghum is capable of accumulating high vegetative DM to grain DM ratios compared with typical grain sorghum, with harvest heights of 1.8 m to 4.6 m (Marsalis 2006). Forage sorghum fertilization amounts are similar to those of corn for silage production (Mortvedt et al., 1996). Dual-purpose (DP) FS has characteristically higher grain harvest indices, similar to that of corn, compared with other FS cultivars when not stressed. Bolsen and Young (1995) reported total DM and grain DM yields of Sorghum Partners 'NK300' (Sorghum Partners, Inc., New Deal, TX) to average 19.8 Mg ha^{-1} and 8.0 Mg ha^{-1}, respectively, at Hays, KS. Forage sorghum variety trials in south-central and western Kansas, from 2003 to 2005, reported that total DM yields of 'NK300' DP FS ranged from 8.4 to 13.6 Mg ha^{-1} on dryland and 17.4 to 19.4 Mg ha^{-1} under irrigation. Grain yields ranged from 2.3 to 6.9 Mg ha^{-1} on dryland and 1.8 to 6.3 Mg ha^{-1} under irrigation. Land O'Lakes DKS59-09 (Land O'Lakes, St. Paul, MN) DP FS achieved similar total DM yields on dryland (6.4 to 13.7 Mg ha^{-1}) and under irrigation (14.3 to 19.5 Mg ha^{-1}) in the same Kansas trials. Grain yields on dryland (0.6 to 7.0 Mg ha^{-1}) and under irrigation (3.0 to 6.4 Mg ha^{-1}) were similar to that of 'NK300' as well (Roozeboom, et al., 2004; Roozeboom et al., 2005; Roozeboom et al., 2006). These data demonstrate the yield variability of DP FS in dryland and irrigated environments, and that reasonable stover DM yields can be achieved even if environmental stresses decrease grain production. Grain harvest index variation of forage sorghum is influenced greatly by the specific environmental stresses, more so than corn.

Brown mid-rib corn and sorghum cultivars were genetically developed to have lower lignin concentrations within the plant, thus making the stover more palatable and digestible for animal feed purposes (Marsalis, 2006). Current processes used to convert LC biomass into liquid biofuel requires heat and acid to remove the non-fermentable lignin component, therefore the reduced lignin content of *bmr* sorghum increases its energy conversion efficiency (Gressell 2008). The *bmr* mutant genes most commonly used for agronomic purposes are *bmr-6, bmr-12* and *bmr-18,* and refer to the reddish-brown pigmentation of the leaf mid-rib of these specific phenotypes (McCollum et al., 2005; Sarath et al., 2008). Decreased total DM yields, plant height, tillering and increased lodging are potential negative characteristics for *bmr* mutated sorghum compared with similar non-*bmr* sorghum varieties (Pedersen et al., 2005). Oliver et al. (2005) reported average lodging of *bmr* FS to be 23%, however Bean et al. (2002) reported lodging to be 87%. McCollum et al. (2005) reported that *bmr* FS varieties produced significantly less total DM (16.8 Mg ha^{-1}) than non-*bmr* FS (19.0 Mg ha^{-1}), PS sorghum (24.0 Mg ha^{-1}) and corn (19.0 Mg ha^{-1}), all of which were irrigated. Lodging potential of *bmr* FS can be minimized by seeding rate and N fertility management. Bean et al. (2003) concluded that lodging of the *bmr* hybrid

‘BMR 100’ increased 25% when N fertilizer rates were increased from 56 to 112 kg ha^{-1}. They also reported that increasing the seeding rate of ‘BMR 100’ from 74,100 to 148,200 seeds ha^{-1} increased lodging by 56.6%, and yields of the *bmr* FS at lower N and seeding rates were not different than yields at the higher rates. Bean et al. (2005) suggested that *bmr* FS may not be able to perform under high heat and drought situations as well as non-*bmr* FS based on a 26% yield decrease in *bmr* cultivars during the 2003 growing season which experienced above normal heat and drought stress. Oliver et al. (2005) found that the *bmr*-6 and *bmr*-12 near isolines produced significantly less total DM yields than those of their wild-type FS lines, but achieve increased DM digestibility in livestock. Brown mid-rib FS cultivars are viable biofuel crops with increased conversion efficiencies compared with other grass crops, but potential reduced total DM yield and increased lodging compared with non-*bmr* sorghum are factors which must be considered when managing this crop.

High-tonnage (energy) sorghum can produce increased levels of LC material, with little to no grain production depending upon the climate, compared with other sorghum cultivars. These are usually classified as hybrid PS FS, which do not initiate reproductive flowering stages until day length is 12 hours and 20 minutes or less (McCollum et al., 2005). Photoperiod sensitive sorghum will not produce grain at most latitudes in the continental United States, except for the very southern regions. The PS characteristic allows these sorghum hybrids to accumulate vegetative DM for longer periods throughout the growing season. They have the ability to recover from high heat or drought stress by resuming growth once environmental conditions become conducive again. Photoperiod sensitive hybrids can be derived from the cross of two photoperiod insensitive parental sorghum lines (Rooney et al., 2007). Soil fertility, planting dates and seeding rates of conventional FS can be used for PS sorghum management

(Marsalis 2006). Dryland and irrigated FS trials from 2003-2004, in south-central and western Kansas, reported that total DM yields of PS ‘NK1990CA’ were equal to or greater than those of the DP FS ‘NK300’ and ‘DKS59-09’ (Roozeboom et al., 2004; Roozeboom et al., 2005). Yields of PS sorghum on dryland ranged from 7.6 to 17.5 Mg ha^{-1} and under irrigation ranged from 15.4 to 21.3 Mg ha^{-1}. Dual purpose FS DM yields during the same trial years ranged from 6.4 to 13.7 Mg ha^{-1} on dryland and 14.3 to 19.5 Mg ha^{-1} under irrigation. These data illustrate that PS sorghum yield variability can be similar to that of conventional forage sorghums under dryland conditions. McCollum et al. (2005) reported DM yields of PS sorghum to be 26% to 43% greater than that of corn, non-BMR, and BMR FS with less overall water use. Blumenthal et al. (2007) stated DM yields of PS sorghum to be 30 Mg ha^{-1} in southern Texas. Low relative lodging has been reported over several site years of variety trial data in Kansas and Texas (Bean and McCollum, 2006; Roozeboom et al., 2004; Roozeboom et al., 2005). Photoperiod sensitive sorghum has characteristicly high lignin content in the stalks, which minimizes lodging, but decreases digestibility in animals, and will likely reduce ethanol conversion efficiencies compared with other FS culitivars. High total DM yields can potentially offset lower ethanol conversion efficiencies.

Sweet sorghum is a specific group of sorghum cultivars which accumulate high levels of fermentable carbohydrates (FC) (15-23%) within the stalk of the plant, which can be extracted and directly converted into ethanol using simple processes (Sarath, et al., 2008; Smith et al., 1987). Utilization for bioenergy conversion processes is higher for sweet sorghum compared with other crops because it produces high biomass and FC yields, along with a small amount of grain. Sweet sorghum requires less water and contains higher FC levels than sugarcane or corn, making it a favorable ethanol production crop for semi-arid temperate climate regions (Reddy et al., 2007). Total FC is comprised of three main sugars; sucrose, glucose, and fructose. Relative percentages of each sugar are 70%, 20% and 10%, respectively (Wu et al., 2008a), but vary depending on the sweet sorghum variety (Prasad et al., 2007). Brix is a widely accepted method of quickly measuring FC content, and has been well correlated to FC content (Tsuchihashi and Goto, 2004). Putnam et al. (1991) found that extracted FC from long season sweet sorghum varieties could produce ethanol yields equal to, or greater than, those of corn grain alone. Sweet sorghum is reported to use significantly less N than other high-biomass yielding crops (Anderson et al., 1995; Bean et al., 2008; Putnam et al., 1991). Harvest timing greatly influences total DM accumulation and FC contents of sweet sorghum. Lodging combined with rapid juice/FC degradation after extraction or killing freeze, are issues which must be considered for harvesting and conversion process management. Almodores et al. (2007), Broadhead (1972), and Zhao et al. (2009) found that total DM yield, brix value, and sucrose content of sweet sorghum was highest when harvested at physiological maturity. Tsuchihashi and Goto (2004) reported single pass FC extraction rates using a triple-roll mill to be approximately 50%, which supports the generally accepted FC extraction efficiency range (45% - 55%) of roller mills. Extraction efficiencies of approximately 75% are achievable with multiple milling procedures, similar to sugarcane milling, or the use of a screw-press. Dry matter yields of sweet sorghum are comparable to PS sorghums. Grain yields are significantly less than commonly produced by grain or DP FS cultivars, and much more difficult to harvest due to the height of the plants (3-5 m). Reddy et al. (2007) and Zhao et al. (2009) supported this by reporting average grain yields of 2.2 to 5.7 Mg ha^{-1}. Total DM yields and brix values of extracted juice can vary greatly with environment and harvest timing. A compilation of yield data for ‘M81E’ sweet sorghum from ten southern U.S. locations across multiple years found DM yield of stalks, FC, and brix juice values to be 23 Mg ha^{-1}, 5.2 Mg ha^{-1}, and 17.0, respectively (Broadhead et al., 1981). 'M81E' is a late maturing variety, resistant to lodging, and was developed as a potential energy crop. Putnam et al. (1991) studied the performance of 13 sweet sorghum cultivars and reported total DM yield (16.1 to 35.8 Mg ha^{-1}), brix values of extracted juice (5.8 to 13.7), harvest stalk moisture (67 to 76%), and extracted FC yields (2.3 to 7.0 Mg ha^{-1}) to vary significantly among cultivars, with long season cultivars achieving the highest yields. These findings are supported by Zhao et al. (2009). Extracted juice storage issues can be overcome by fermenting the FC immediately, or storing the juice at temperatures near freezing to impede microbial activity and breakdown of FC (Wu et al., 2008a). Sweet sorghum has the potential to be an excellent diversified biofuel crop able to fill the needs of multiple bioenergy conversion process across many environments with reduced energy requirements.

Perennial Warm-Season Grass Yields

Perennial WS C4 grass crops are becoming the focus of increased research for the LC biofuel industry due to their relatively low annual input requirements, reduced management needs, and wide adaptability for production on marginal to highly productive land. Shifflet and Darby (1985) stated that WS perennial grasses are able to be productive in stressful environments due the deep root system's ability to acquire water and nutrients. Originally occupying a vast native establishment area throughout the North American prairie, switchgrass (*Panicum virgatum* L.) and big bluestem (*Andropogon geradii* Vitman) are currently popular choices for animal forage feedstock, but also as LC feedstock production for the developing cellulosic ethanol industry. Although not native to the U.S., *Miscanthus x giganteus* (subsequently referred to Miscanthus) is another prospective perennial C4 WS grass for cellulosic bioenergy production. Extensive production research has been ongoing since the early

1980’s in Europe, but research in the U.S. is limited due to its recent introduction (Lewandowski et al., 2003). Perennial grasses harvested after dormancy have lower moisture content (<20%) and nutrient concentrations in the aboveground biomass due to translocation, compared with annual grass crops harvested after physiological maturity. Perennial grasses have the ability to fit an important production role in the LC biofuel industry, but further research of their true production capabilities relative to annual crops is needed.

Switchgrass has been the center of focus in the United States as a perennial WS C4 grass to supply LC feedstock, and was chosen by the U.S. Department of Energy in 1991 as a model herbaceous energy crop (McLaughlin, 1992). Switchgrass has several very desirable biofuel cropping system traits, such as high DM production across many environments, productivity on highly-erosive and marginally productive land, and relatively low water and fertilizer requirements compared with annual crops (McLaughlin et al., 1999). Vogel et al. (1985) stated that two main ecotypes of switchgrass occur across its native geographic area; a thick stemmed lowland type suited for warm, moist environments, and a thin-stemmed upland type found in the mid to northern latitude areas. Switchgrass is an open-pollinated seed producing species, but can also reproduce vegetatively from its deep root system as well. One disadvantage of switchgrass, similar to other perennial grasses, is that establishments can be difficult to achieve and full production may take two to three years (Sanderson and Adler, 2008). Stand establishment can be enhanced by proper seeding depth (0.6-1.2 cm), seeding rates (11 to 13.4 kg pure live seed (PLS) ha^{-1}), seed bed prepartation, and control of weed species during establishment year (Nyoka et al., 2007). Weed control can be accomplished by eliminating N fertilizer application in the establishment year, select herbicides applied at labeled rates and timing, and burning at the proper frequency to increase vigor (Cuomo et al., 1997; Nyoka et al., 2007; Sanderson et al., 2004). Compiled yield data from several sites across the United States have shown switchgrass yields to range from 9.9 to 23.0 Mg ha^{-1}, with an average DM yield of 13.4 Mg ha^{-1} (McLaughlin and Kszos, 2005). Sanderson et al. (2004) reported switchgrass DM yields to range from 7.65 to 10.89 Mg ha^{-1} in 1998 and 5.02 to 6.68 Mg ha^{-1} in 1999, respectively, across six burn and herbicide treatments. In the same study, big bluestem achieved DM yields of 3.56 to 7.68 Mg ha^{-1} in 1998 and 2.51 to 6.02 Mg ha^{-1} in 1999, respectively. McLaughlin et al. (1999) reported the most promising switchgrass cultivar for the mid latitude area of the United States to be the lowland type 'Kanlow', which had an average DM yield of approximately 16 Mg ha^{-1}. The study also found the single cut harvesting systems yielded similarly to that of the two-cut harvesting approach, and removed about one-third of the total N. Mulkey et al. (2007) supported the single-cut harvesting approach after first killing frost, finding highest DM yield and stand sustainability of switchgrass and big bluestem grass mixtures with this harvesting method. The reduced N removal can be attributed to perennial WS grass' ability to translocate mobile nutrients and carbohydrates into the crowns and root systems late in the growing system. Nutrient translocation of these grasses finds them generally unresponsive to phosphorus (P) and potassium (K) fertilizer application, but a positive N response has been reported (Hall et al., 1982). The study also found that switchgrass and big bluestem yields were similar when averaged over three site years and N treatment rates, but both species had a positive DM yield response to N fertilizer treatments through 75 kg N ha^{-1}, and some through 150 kg N ha^{-1}. Although switchgrass yields will vary across environments and management practices, it has the potential to produce relatively high biomass yields with low input costs, thus making it an ideal LC bioenergy crop.

Big bluestem is found in wide-spread native establishments across the North American Tallgrass Prairies as well. Big bluestem is a perennial WS C4 bunchgrass with harvest heights of 0.9 to 1.8 m, and accumulates 65 to 75% of its aboveground DM from June through August (Bartholomew et al., 1995). Like switchgrass, big bluestem is well adapted to a wide array of environmental conditions, preferring well drained, deep soils, but can achieve productivity in dry or low fertility situations (Tober et al., 2008). Knapp (1985) stated that big bluestem is a drought tolerant species with the ability to maintain high rates of carbon accumulation over a wider range of temperatures with lower available water than switchgrass. Stand establishment with big bluestem can also be challenging, but seeding (11 to 13.4 kg PLS ha^{-1}) and establishment management similar to that of switchgrass can improve stands significantly. Masters (1997) reported that the preemergence application of *S*-metolachlor or atrazine herbicides, in the establishment year, can increase DM yields and overall stand establishment, but the response will vary depending upon weed species and pressure. Reproduction is both vegetative from rhizomes, as well as from seed, which can yield 100-200 kg ha^{-1}. ‘Kaw’ big bluestem is a long season variety which originated from several native lines found in the Flint Hills of east central KS, near Manhattan (Tober et al., 2008). Response to P and K fertilization is subject to the soil nutrient levels, but a response to N fertilization has been reported similar to that of switchgrass. Hall et al. (1982) reported total DM yields of big bluestem to be slightly over 4 Mg ha^{-1} with no N fertilization and above 7.5 Mg ha^{-1} with 150 kg N ha^{-1} applied in the growing season. Total DM yields and yield response to N, P, and K were similar to that of switchgrass. Bartholomew et al. (1995) reported 10 year average DM yields of established ‘Kaw’ big bluestem and ‘Kanlow’ switchgrass to be 5.3 and 4.5 Mg ha^{-1}, respectively, with 168 kg N ha^{-1} in Ohio. Application of 75 kg N ha^{-1} was found to maximize DM yields of big bluestem (6.9 Mg ha^{-1}) and switchgrass

(7.6 Mg ha^{-1}) in Iowa (IA) (Barnhart, 1989). Tober et al. (2008) reported 10-year average total DM yields of 'Kaw' big bluestem to be 4.0 Mg ha^{-1} across six sites in north central United States, 11% less than the highest yielding variety 'Sunnyview'. Overall yield variability and management requirements of big bluestem are similar to that of switchgrass. Big bluestem has a yield potential equal to, or below, those of switchgrass with similar environmental factors and management intensity.

Miscanthus, a perennial WS C4 grass native to Asia, is a sterile hybrid resulting from the cross of *Miscanthus sacchariflorus* and *Miscanthus sinensis,* and most commonly propagated vegetatively by dividing the underground rhizomes (Sanderson and Adler, 2008). High DM yields and low N requirements, compared with annual crops, make this an ideal crop for renewable biofuel production. Miscanthus has been found to be productive for 14 or more years in long term European studies (Christian et al., 2008; Lewandowski et al., 2000). Establishment year biomass production is usually low, with increased annual production during the initial three to five years of establishment (Miguez et al., 2008). Christian et al. (2008) found that harvested dry matter production of Miscanthus to be 1.6, 7.5, and 10.8 Mg ha^{-1} in the first three years after establishment, respectively. Harvested dry matter yields across years four through 14 of the study averaged 14.5 Mg ha^{-1} with no significant yield difference among three N rates (0, 60 and 120 kg N ha^{-1}). Clifton-Brown et al. (2004) reported a compilation of established dry matter yields, across 27 dryland and irrigated sites in Europe, to range from 17 Mg ha^{-1} to 49 Mg ha^{-1} when harvested within two months of the growing season end. When harvest was delayed for more than two months, dry matter yields ranged from 10 Mg ha^{-1} to 30 Mg ha^{-1}, likely due to leaf losses. Boehmel et al. (2008) found that Miscanthus achieved higher yields (18.1 vs. 14.1 Mg ha^{-1}) than that of 'Kanlow' switchgrass when grown under the same conditions in southwestern

Germany. Lewandowski et al. (2006) reported Miscanthus annual dry matter yields of 8 to 38 Mg ha^{-1} at four site locations in southwest Germany starting with harvests in the second year of establishment. Studies conducted in Illinois from 2004-2006 found established peak dry matter yields of Miscanthus to be 38.1, 51.3, and 60.8 Mg ha^{-1}, respectively at the north, south and central regions of the state (Heaton et al., 2008). Yield of Miscanthus has not been widely studied in the United States, although research in Europe has shown the excellent yield potential of the crop over other perennial WS grass crops (i.e. switchgrass), and annual crops.

Annual vs. Perennial Crop Yields

Biomass cropping system studies often focus on one type of crop (annual or perennial) due to differences in environmental yield potential, relative productivity of the soil, and management practices. Hallam et al. (2001) researched both annual and perennial C4 crops at two locations in Iowa over a five year period with 140 kg N ha^{-1} annually; one highly productive row-crop site (Ames), and a marginal pasture land site (Chariton). They reported average total DM yields for 'M81E' sweet sorghum, FS, corn, switchgrass, and big bluestem to be 17.5, 15.7, 14.0, 10.6 and 8.9 Mg ha^{-1}, respectively, at the Ames site. Total DM yields at the Chariton site were 18.0, 15.6, 10.6, 10.3, and 7.3 Mg ha^{-1}, respectively. Based on yield and production costs, the study concluded that the lowest cost of biomass production can be achieved with annual sorghums and perennial switchgrass crops. Boehmel et al. (2008) conducted a study comparing total DM and energy yields of C4 annual and perennial grass crops (energy corn, Miscanthus, and 'Kanlow' switchgrass) in southwest Germany. Highest total DM yields of Miscanthus and energy corn were not different, and were produced with 80 and 120 kg N ha^{-1} respectively. Switchgrass produced the lowest DM yields of the perennial grasses, with maximum yields at 80 kg N ha^{-1}, not different than Miscanthus with no added N. Energy use efficiency (unit of energy output per unit of energy input) of the three crops was highest for the energy corn and switchgrass with no added N fertilizer. Miscanthus with 40 kg N ha^{-1} had energy use efficiency values not different than switchgrass with 40 kg N ha^{-1}, and corn with 120 kg N ha^{-1}. Bioenergy crops must not only be evaluated by their total potential DM production, but on their estimated energy output as well.

Ethanol Conversion Yields

In the United States, the predominant bioenergy conversion process uses carbohydrates from grains for fermentation into ethanol fuel. Future technology development will utilize carbohydrates from LC biomass portions and FC from sweet sorghum or sugar cane to produce ethanol as well. Starch conversion efficiencies for grain and LC biomass to ethanol processes have increased over the last decade as technology advances. Putnam et al. (1991) reported ethanol conversion yield for corn grain to be 371 L Mg^{-1} grain. Current dry-grind ethanol conversion processes yield 417 L ethanol Mg^{-1} corn grain (Wang et al., 2005). Corn hybrid selection, and starch content of the grain, will determine actual grain ethanol yields. Sorghum grain has similar ethanol conversion yields as corn grain. Wang et al. (2008) found that sorghum grain starch content can vary from 64% to 74% across different sorghum cultivars, and ethanol yields can differ by 7.4% across grain samples with similar starch levels. Plant biomass, on average, contains cellulose (38-50%), hemi-cellulose (23-32%) and lignin (15-25%), which vary in composition percentage among different crop species and cultivars. Ethanol conversion yields from LC biomass differ due to differences in cellulosic and hemi-cellulosic levels. Initial LC to ethanol conversion technology yielded 280 L ethanol Mg^{-1} dry stover, but future process development is expected to achieve conversion yields of 370 L Mg^{-1} or higher (McAloon et al. 2000). Low-lignin content crops like *bmr* sorghum cultivars will likely have higher conversion efficiencies than high-lignin PS sorghums. Ethanol production from FC extracted from sorghum or sugar cane is a low input process with conversion efficiencies of 90% or greater (Wu et al., 2008a). The extracted FC to ethanol conversion yield for sweet sorghum is generally accepted to be 1.76 kg FC L^{-1} ethanol (Anderson et al., 1995; Putnam et al., 1991; Undersander et al., 1990), but increased efficiencies of 1.4 kg FC L^{-1} may be achievable with future technological advances.

Nutrient Concentrations and Removal

High biomass removal for renewable energy production will potentially lead to depletion of soil macro-nutrients (N, P, and K) if fertilizers are not used to replace the removed minerals. Fertilizers generally require high energy input to extract, transport, and/or produce, thus lowering the net energy return of the bioenergy system if required at high levels. Fertilizer costs are often reflected by concurrent petroleum prices worldwide. Nitrogen is considered to be the highest fertilizer energy input for many grass cropping systems, therefore receives the most focus in bioenergy systems. Semi-arid regions of the western Great Plains often have high soil test K values which do not require fertilizer replenishment in current cropping systems. Recent high volatility of fertilizer prices has increased the importance of understanding the nutrient removal rates of biofuel crops used as feedstock for renewable energy conversion processes.

Nutrient concentrations of biomass can affect the efficiency of energy conversion processes. High K and ash contents of biomass can corrode and foul boiler systems used to create steam for electricity production (Lewandowski and Kicherer 1997). Nitrogen is generally undesirable for thermochemical energy conversion processes as well. Increased N accumulation in grain is associated with higher protein levels. Wu et al. (2008b) alluded to the fact that protein and starch concentrations in grain are inversely related, therefore low protein levels allow for grain to accumulate increased starch amounts. They also commented that high starch levels allow for increased ethanol conversion efficiencies, higher ethanol yields, and reduced leftover residues after fermentation. Nutrient concentrations in biomass are important considerations when choosing crops to supply biomass for specific conversion processes.

Nutrient removal can be significantly lower in perennial WS grass crops if harvest timing is in conjunction with the nutrient and carbohydrate translocation (Boehmel et al., 2008). In the fall, WS perennial grasses translocate minerals and carbohydrates into the crown and rhizome components for over-wintering and spring regrowth (Sanderson and Adler, 2008). Potassium concentrations of stover can vary significantly from year to year, which is believed to be caused by precipitation leaching K from aboveground DM (Sander, 1997). Himken et al. (1997) reported N, P, and K translocation from aboveground Miscanthus biomass into rhizomes to be 21-46%, 36-50%, and 14-30%, respectively. If harvested before fall dormancy, such as with multiple annual harvests, nutrient concentrations and total removal will increase significantly.

In current grain based ethanol systems, nutrients are removed by the harvested grain, but remain in the stover portion of the crop. Corn biomass used for ethanol, or other bioenergy, production will have nutrient removal amounts similar to those of corn harvested as silage. Maloney et al. (1999) found N removal in corn grain to generally be lower for CC (122 kg N ha^{-1}) than corn rotated with soybeans (131 kg N ha^{-1}) with 180 kg N ha^{-1} fertilizer. Total N removal by silage harvesting showed similar trends found with grain N removal. Continuous corn and rotated corn (RC) accumulated 160 kg N ha^{-1} and 171 kg N ha^{-1}, respectively, in the total biomass harvested for silage. This trend can be explained by the overall higher grain and biomass yields of corn rotated with soybeans. Hossain (2006) reported nutrient removal of corn grain to be 127 to 175 kg N ha^{-1}, 32 to 35 kg P ha^{-1}, and 34 to 38 kg K ha^{-1} at an 11 Mg ha^{-1} grain yield.

Riedell et al. (1998) reported corn stover at tassel to have N concentrations of 13, 000 ppm at high and intermediate fertilizer input levels, while N concentrations of stover with no fertilizer were significantly less (9, 900 ppm). Low input system stover P concentrations were numerically higher for CC (1800-2500 ppm) than rotated corn (1600 – 1900 ppm), but differences at high and intermediate fertilizer rates were minimal. No significant K concentration interactions were reported across rotation and fertility treatments in the study. Soil test nutrient levels will affect the absorption, and total concentration, of specific mineral nutrients within the plant components.

Miscanthus has been found to have relatively low fertilizer requirements, making it a very nutrient efficient energy crop (Beale and Long, 1997; Lewandowski and Schmidt, 2006). Clifton-Brown et al. (2007) observed that delaying harvest from immediately after first killing freeze in the fall, to early spring, reduced N stover concentrations from 7000 to 4000 ppm, P concentrations from 1000 to 600 ppm, and K concentrations from 5300 to 3900 ppm. The nutrient concentration reduction supports the idea that perennial WS grasses translocate nutrients from the stover to rhizomes late in the season. Gibson and Barnhart (2007) reported P and K removal rates of 0.75 and 6 kg Mg^{-1} dry stover, respectively, in Iowa. Based on total nutrient removal, Clifton-Brown et al. (2007) reported that delaying harvest until early spring reduced total N, P and K removal to 51, 8.3 and 7.9 kg ha^{-1}, respectively. Fall harvests were found to have higher respective removal amounts of 94, 15, and 69 kg ha^{-1}. Lewandowski and Schmidt (2006) concluded Miscanthus has a strong yield response with N rates of 0-50 kg ha^{-1}, but maximum production occurred at 114 kg N ha^{-1}. Leaf DM makes up 60% of the total harvested DM in the establishment year, and contains higher N concentration (7600 ppm) than the leaf and stem components combined (5600 ppm) (Cosentino et al., 2007). This suggests that N concentrations of Miscanthus biomass in the establishment year may be higher than following years, however low stover yield in the first year will minimize total N removal. If harvested after dormancy in subsequent years, leaf DM makes up 25% or less of the total harvested DM due to leaf senescence after freeze, thus reducing N removal from leaf components.

Switchgrass and big bluestem translocate mobile nutrients and carbohydrates to crowns and root systems in the fall much like Miscanthus. McLaughlin et al. (1999) reported N concentration of ‘Kanlow’ biomass, using a two-cut and single-cut harvest method after dormancy, to be 3200 and 2500 ppm, respectively. Respective total N removal for the two-cut and single-cut systems were 152 kg ha^{-1} and 51 kg ha^{-1}, with a slight DM yield advantage for the two-cut system. Studies have found that 58% of total N in big bluestem stover is translocated to the stem bases during senescence in the fall, and stover N concentration is 2000 ppm in late fall compared with 16, 600 ppm in May of the same year when growth is rapid (Clark, 1977; Hayes, 1985). Hayes (1985) also reported perennial WS grasses can increase N allocation to rhizome portions from the stems to protect the plant during drought stress. Nitrogen concentrations and total N removal with stover may be low within the growing season if harvested after periods of severe drought. Phosphorus and K concentrations in harvested stover will vary depending upon; species and genotype, soil nutrient levels, and production environment. El-Nashaar et al. (2009) reported harvested stover P and K concentrations of several switchgrass genotypes to range from 1300 - 6400 ppm and 6200 – 15, 800 ppm, respectively, across multiple locations. Research by Cassida et al. (2005) supports these findings with reported stover P concentration ranging from 900 – 1700 ppm and total P removal for lowland and upland genotypes to be 12 and 8 kg ha^{-1}, respectively. Parrish et al. (1996) reported that K concentrations in switchgrass harvested post-freeze were 27% less than if harvested pre-freeze. Like Miscanthus, P and K levels of switchgrass are shown to be reduced significantly by harvesting after an over-wintering period, compared with immediately after the first killing freeze (Adler et al., 2006).

Nutrient removal by FS is considered to be similar to that of corn harvested for silage/biomass purposes. Although FS can be productive at low input levels, it usually responds well to fertilizer. Buxton et al. (1999) suggested that N and K concentrations in sorghum are higher when sorghum growth is limited by water stress, suggesting that under stress, nutrient accumulation rates are higher than DM accumulation. The study also reported N concentrations in stover to increase (8800 – 11, 500 ppm) with increasing N fertilizer rates, but K concentrations (13, 775 ppm) were not different across N rates. Bean et al. (2008) reported total N removal for FS cultivars to not be different, with average uptake of 173 kg ha^{-1} under irrigation. A study by McCollum and Bean (2003) found total P removal by corn, FS, and BMR FS to be similar (approximately 42 kg ha^{-1}) when harvested for silage. Phosphorus removal was higher (58 kg ha^{-1}) for PS sorghum cultivars due to higher total DM yields. Nutrient concentrations of FS and high-tonnage PS sorghum are generally similar, with total removal depending upon total DM yields.

Sweet sorghum nutrient removal must be accounted for in the grain, stover, and extracted juices as utilized for different energy conversion processes. Sweet sorghum has been found to require less N than corn or other sorghum types. Anderson et al. (1995) reported that sweet sorghum required less than 50% total N to produce similar ethanol yields as corn. These data are supported by Bean et al. (2008) which found sweet sorghum to remove 62% of the total N removed by grain or FS types with no difference in DM yield. It has been suggested that sweet sorghum yielding 11 – 16 Mg ha^{-1} will remove N, P and K at the rate of 112, 45, and 202 kg ha^{-1}, respectively (Undersander et al., 1990). Although nutrient removal data is not readily available for sweet sorghum juice, Fenzhou (1989) found P and K concentrations across multiple sweet sorghum varieties to be 35-110 ppm and 904-3087 ppm respectively. The structural carbohydrates of the stalk will contain a majority of the N, P and K, so removal by extracted juice will likely be low. When total biomass harvesting is evaluated, sweet sorghum N removal is lower than corn or other forage sorghum crops, but total P and K removal is similar, supporting the generalization that sweet sorghum requires lower energy inputs for energy production compared with other annual crops.

Research Question and Justification

Recent increases in the demand for renewable energy has stimulated the use of agricultural commodities, mainly corn grain, for ethanol production in the United States. Corn and sorghum grain provide high density energy forms which can be converted to alcohol fuel at relatively high efficiencies with current technology. The recent surge in demand for grain has impacted other sectors which rely on this energy source, noticeably livestock and foreign exports. As renewable energy demands continue to increase, alternative alcohol fuel conversion processes will require large sources of LC biomass and FC. A variety of annual and perennial C4 crops can be grown in current agronomic cropping systems to potentially meet the energy requirements. Research data comparing annual and perennial crop performance, along with nutrient removal data, is limited. Agronomic and renewable energy producers need to be able to estimate DM yields, ethanol yield, and nutrient removal by current and alternative biofuel crops for production and logistical cost estimation analyses. Environment, energy inputs, harvesting logistics, specific energy conversion processes, and economics will ultimately dictate which crops are used for renewable fuel production.

The goal of this project is to explore multiple annual and perennial crops which have been suggested for biofuel production potential in northeast Kansas. Field research will investigate grain and stover yields, along with nutrient removal by the selected crops at two locations over two years. Sweet sorghum will be pressed and extracted juice will be analyzed for FC content and yield. Ethanol yield of individual crops will be calculated using current estimated ethanol conversion rates and stover, grain and/or FC yields from the field trials.

Therefore the objectives of this research are to:

i.) evaluate the grain and/or stover DM, yield of select annual and perennial biofuel crops grown under the same soil and weather conditions,

ii.) evaluate the juice extraction efficiency and subsequent FC yield of sweet sorghum,

iii.) evaluate the estimated ethanol production of annual and perennial biofuel crops, and

iv.) evaluate nutrient (N, P, and K) concentrations in grain, stover, and/or sweet sorghum juice, and total nutrient removal calculated from nutrient concentrations and respective component yield.

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CHAPTER 2 – Biomass, Fermentable Carbohydrate, and Estimated Ethanol Yields

Abstract

Increasing demand for renewable fuel sources has stimulated the need for alternative crop biomass production. A study was conducted to determine grain, stover, total biomass, and estimated ethanol yields of annual and perennial C4 crops at two dryland locations in northeast Kansas in 2007 and 2008. Sweet sorghum [*Sorghum bicolor* (L.) Moench] fermentable carbohydrate (FC) extraction rates and yields of were also evaluated. Plots, each consisting of four replications, were established at Troy and Manhattan in 2007. This study included corn (*Zea mays L.*) grown continuously (CC) and rotated (RC) with soybean [*Glycine max* (L.) Merr.], five sorghum cultivars; brown mid-rib (*bmr*), photoperiod sensitive (PS), sweet, and two dual-purpose (DP) forage cultivars, rotated with soybean, as well as three perennial warm season (WS) grasses; switchgrass (*Panicum virgatum* L.), big bluestem (*Andropogon gerardii* Vitman), and Miscanthus (*Miscanthus x giganteus*). Corn and sorghum plants were harvested after physiological maturity or before first killing freeze. In addition, sweet sorghum stalks were pressed to extract juices. Perennial grasses were harvested after dormancy. Highest grain yields were achieved with corn across both years and locations with yields averaging 10.1 Mg ha^{-1}. Total biomass yields were greatest for sweet sorghum (32.6 and 28.2 Mg ha^{-1} in 2007 and 2008, respectively) and PS sorghum (26.8 Mg ha^{-1} in 2007). Sweet sorghum extracted FC yields averaged 4.8 Mg ha^{-1}. Perennial grass biomass yields ranged from 7.7 to 12.8 Mg ha^{-1} in 2008, the second year of establishment. Highest average estimated ethanol yields were achieved with

sweet sorghum (9920 L ha^{-1}). These results indicate the highest total biomass and estimated ethanol yields for renewable fuel production can be achieved from sweet sorghum.

Introduction

The current renewable fuel industry in the United States has been developed to use starch from corn or sorghum grain to produce ethanol. The increased demand of corn for ethanol production has reduced the supply available for other markets, including livestock and exports. As ethanol conversion process technology advances, lignocellulosic (stover) biomass and FC extracted from sweet sorghum or sugar cane (*Saccharum officinarum)* can supplement corn grain. Grass crops with C4 physiology have been selected for renewable fuel production due to their characteristic high biomass yields, reduced nutrient requirements, and ability to produce in water limited, or marginally productive environments. These selected crops include both annual and perennial crops which can be integrated into current agronomic cropping systems.

Few studies have focused on the direct comparison of biomass yields of annual and perennial crops due to their management differences and overall production characteristics. Hallam et al. (2001) reported average total biomass yields of sweet sorghum, forage sorghum (FS), corn, switchgrass, big bluestem to be 17.5, 15.7, 14.0, 10.6, and 8.9 Mg ha^{-1}, respectively on a highly productive site in Iowa. The study found yields of the same crops on a marginally productive site to be 18.0, 15.6, 10.6, 10.3, and 7.3 Mg ha^{-1}. When yields were analyzed with energy inputs, the study concluded that lowest cost biomass production could be achieved with annual sorghums or perennial switchgrass crops. Boehmel et al. (2008) found total biomass yields of energy corn and Miscanthus to be similar with 80 and 120 kg N ha^{-1}, respectively, which were higher than switchgrass biomass yields in the same study.

Corn and sorghum are common annual crops used for grain and/or forage production throughout Kansas, and the Great Plains, due to their wide range of adaptability to dryland and irrigated production systems. Roozeboom et al. (2007) reported average dryland corn grain yields in northeast Kansas and irrigated corn yields across the state to be 7.0 Mg ha^{-1} and 11.5 Mg ha^{-1}, respectively. Growing corn, or sorghum, in a rotation with soybean has been shown to significantly increase yields by multiple studies (Baldock et al., 1981; Buxton et al., 1999; Hicks and Peterson, 1982; Peterson and Varvel, 1989; West et al., 1996). Sorghum cultivar selection can be based upon the final commodity desired. Dual-purpose FS accumulates greater vegetative to grain dry matter (DM) ratios than grain sorghum, but has increased grain DM production compared with common FS. Brown mid-rib FS was genetically developed to accumulate reduced lignin concentrations within the plant, thus increasing the digestibility as a livestock forage (Marsalis, 2006). The reduced lignin characteristic of *bmr* sorghum cultivars will likely increase their cellulosic ethanol conversion efficiencies compared with other FS cultivars since lignin cannot be utilized for ethanol production. Photoperiod sensitive sorghum is capable of producing high lignocellulosic (LC) DM yields without the production of grain at most latitudes in the United States. These high-tonnage sorghum cultivars do not initiate reproductive flowering until the day length is 12 hours and 20 minutes or less, which is shortly before the first killing frost in much of the United States, except far southern regions (McCollum et al., 2005). Total biomass yields of PS sorghum have been reported to be 26% to 46% greater than corn, non-*bmr* and *bmr* FS cultivars, with less overall water use (McCollum et al., 2005). The high lignin content of PS sorghum minimizes lodging issues, but will likely reduce cellulosic ethanol conversion efficiencies. Sweet sorghum cultivars accumulate high levels of FC (15-23%) within the stalk, which can be extracted and directly converted into ethanol (Sarath et al., 2008; Smith et al., 1987). Sweet sorghum produces relatively small amounts of grain, but high yields of LC biomass, increasing its utilization ability as an energy crop. Putnam et al. (1991) found that long season sweet sorghum cultivars produced the highest total biomass and FC yields. They also reported that when extracted FC were converted into ethanol, sweet sorghum achieved higher ethanol yields than corn grain alone. Fermentable carbohydrate extraction rates from sweet sorghum stalks with a triple-roll mill is generally accepted to be 45% - 55% (Tsuchihashi and Goto, 2004), but alternative extraction processes can achieve greater efficiencies. Unlike corn, sorghum has the ability to accumulate LC biomass, even if grain DM accumulation is reduced by water stress, making it a viable crop for biofuel production in water limited environments (Fribourg, 1995; Unger and Wise, 1979).

Perennial WS C4 grasses have become the focus of many renewable fuel studies due to their low input requirements, reduced management needs, and adaptability to many environments. Switchgrass was selected as a model herbaceous energy crop by the U.S. Department of Energy in 1991, and has received focus as a future feedstock source for cellulosic ethanol production (McLaughlin, 1992). Switchgrass is native to the prairies of North America, and has been reported to achieve biomass yields ranging from 9.9 to 23.0 Mg ha^{-1} across several U.S. study sites (McLaughlin and Kszos, 2005). Big bluestem is another native grass found on the North American prairies which achieves biomass yields similar to, or slightly less than, those of switchgrass with minimal energy inputs (Barnhart, 1989; Sanderson et al., 2004). Miscanthus is a sterile hybrid grass native to Asia. Studies focusing on the utilization of Miscanthus as a fuel source for steam and power generation have been conducted in Europe since the early 1980's. European research has reported high biomass production (17 to 49 Mg ha^{-1}) from established stands for 14 years or more (Christian et al., 2008; Clifton-Brown et al., 2004; Lewandowski et al., 2000). Although research data for Miscanthus in the United States is minimal, recent studies conducted at three locations in Illinois reported peak biomass yields of 38.1 to 60.8 Mg ha^{-1} from established stands (Heaton et al., 2008). Harvestable production from perennial WS grasses can take two to five years depending upon the specific cultivar and establishment success. Perennial WS grasses generally require less fertilizer inputs to achieve full biomass production due to their ability to translocate carbohydrates and mobile nutrients into the underground crown and rhizome portions of the plant in the fall before dormancy; therefore harvest timing should be managed accordingly.

Ethanol conversion process technology has allowed conversion efficiencies to increase over the last decade, and future development is expected. Current dry-grind ethanol conversion processes yield 417 L ethanol Mg^{-1} corn grain (Wang et al., 2005). Sorghum grain conversion rates are similar. Conversion rates of LC biomass, a combination of cellulose, hemi-cellulose, and lignin, vary from 280 to 370 L ethanol Mg^{-1} DM depending on the individual conversion process and DM component composition (McAloon et al., 2000). The extracted FC conversion rate used for sweet sorghum, or sugar cane, is generally accepted to be 1.76 kg FC L^{-1} ethanol (Anderson et al., 1995; Putnam et al., 1991; Undersander et al., 1990), but efficiencies up to 1.4 kg FC L^{-1} ethanol may be attainable with technological advances.

The objectives of this study were to evaluate the production of annual and perennial C4 biofuel crops based upon grain, stover, total biomass, and estimated total ethanol yields; as well as FC extraction rates and yields of sweet sorghum at two locations in northeast Kansas.

Materials and Methods

Research was conducted in 2007 and 2008 at two dryland locations in northeast Kansas; Troy (39°77’N, 95°12’W) and the Kansas State University (KSU) Agronomy Research Farm at

Manhattan (39º11’N, 96º35’W). Soil types included a Kennebec silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludolls) at Troy, and an Ivan, Kennebec, and Kahola silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludolls) at Manhattan. Soil samples were taken at the 0-15 cm surface and 15-30 cm depth at both locations before planting in April 2007 to analyze organic matter (OM), pH, P, K, and N [ammonia (NH_3) and nitrate (NO_3)] (Table 2.1). Samples at each location were composed of 15 individual soil cores representatively taken across each site area. Phosphorus levels at Manhattan at the 0 – 15 cm and 15 – 30 cm soil depths were 15 and 6 parts per million (ppm), respectively. Although the P levels were below the critical soil test level (20 ppm), they were not addressed for the 2007 growing season. All crops were no-till planted at each location. Cumulative in-season growing degree units (GDUs), precipitation amounts for both site years, and 30-year normals, were based on individual location weather station data (High Plains Regional Climate Center, 2008). Growing degree units were calculated using maximum temperatures (T_{max}) of 29.4º C and 38º C for corn and sorghum, respectively. Minimum (T_{min}) and base (T_{base}) temperatures of 10º C were used for both crops.

The study was designed as a randomized complete block experiment with four replications at each location. Individual plot size was 6.1 m wide by 10.7 m long. The corn hybrids for 2007 and 2008 were Pioneer ‘33K40’ (Bt) and Pioneer ‘33K44’ (Bt), respectively, both of the same parent family with relative maturity of 114 days (Pioneer Hi-Bred International, Johnston, IA). Sorghum cultivars include: Crosbyton ‘GW8528’ (Crosbyton Seed Co., Crosbyton, TX) BMR FS, Land-O-Lakes ‘DKS59-09’ (Land O’Lakes, St. Paul, MN) DP FS, Mississippi State ‘M81E’ (Mississippi State Univ., Mississippi State, MS) sweet sorghum, Sorghum Partners ‘NK300’ (Sorghum Partners, Inc., New Deal, TX) DP FS, and Sorghum Partners ‘1990CA’ PS sorghum. Soybean varieties planted for rotational purposes included Garst

‘3824RR’ (Garst Seed Co., Slater, IA) at Troy in 2007 and KSU Foundation ‘KS3406RR’ (Kansas State Univ., Manhattan, KS) at Troy in 2008 and Manhattan both study years. Perennial grass species included; ‘Kanlow’ switchgrass, ‘Kaw’ big bluestem, and Miscanthus.

Annual crops were planted in April and May of each year with a no-till row crop planter on 76.2 cm row spacing (Tables 2.2 and 2.3). Soybean was the previous crop for all annuals in both years, except for CC in 2008 which was planted into the 2007 CC residue.

Perennial WS grasses were established in May and June of 2007 into soybean residue. Switchgrass and big bluestem were seeded on 16 May at Troy and 14 May at Manhattan with a Truax FLXII-88 (Truax Company, Inc., New Hope, MN) grass drill on 20.3 cm row spacing. Grasses were seeded at a depth of 0.6 to 1.3 cm. Bulk seeding rates were 7.9 kg ha^{-1} (4.0 kg ha^{-1} pure live seed (pls) for the switchgrass and 20.2 kg ha^{-1} (6.3 kg ha^{-1} pls) for the big bluestem. Miscanthus was planted on 11 June and 12 June at Manhattan and Troy, respectively. Individual plants were hand transplanted from the greenhouse to field plots at a population of 6148 plants ha^{-1} using a 1.2 m by 1.0 m grid spacing. Switchgrass in the first replication at the Manhattan site was replanted on 2 May 2008 due to very poor establishment in 2007. Planting methods were the same as the 2007 establishment.

Weed control in annual crops at Troy and Manhattan was accomplished by the use of labeled rates of pre- (PRE-) and post-emergence (POST-) herbicides along with hand weeding as needed to minimize weed pressure throughout the growing season (Tables 2.4 and 2.5). Herbicides were applied with an all-terrain vehicle mounted boom sprayer or tractor mounted boom sprayer at recommended carrier volume rates and adjuvant concentrations. POST-herbicide applications on sorghum at Manhattan in 2008 were accomplished with a tractor mounted “lay-by” hooded sprayer to avoid crop damage.

Weed control in perennial WS grass crops was accomplished by the use of herbicides, mowing, and hand weeding as necessary to minimize weed pressure throughout the 2007 and 2008 growing seasons. An ATV mounted boom sprayer or a manual "back-pack" sprayer were used for herbicide applications depending upon growth stage. Plots at Troy were treated with 1.7 kg ha^{-1} atrazine [2-chloro-4-(ethylamino-6-(isopropylamino)-s-triazine] in Fall 2006, and 0.47 kg ha^{-1} glufosinate [2-amino-4-(hydroxymethylphosphinyl) butanoic acid monoammonium salt] on 19 May 2007 as a PRE-burndown. Plots at Manhattan received 1.1 kg ha^{-1} glyphosate [*N*-(phosphonomethyl)glycine] on 14 May 2007 as a PRE- burndown. Switchgrass and big bluestem were mowed with a sickle mower at a height of 10 cm, to control broadleaf weeds, on 6 July and 9 July 2007 at Manhattan and Troy, respectively. Perennial grasses were treated with 0.56 kg ha^{-1} 2, 4-D dimethylamine salt [(2, 4-dichlorophenoxy)acetic acid] plus 0.94 L ha^{-1} crop oil concentrate (COC) on 7 Aug. 2007 at both locations for further suppression of broadleaf weeds. In 2008, switchgrass and big bluestem were treated with 0.42 kg ha^{-1} diglycolamine salt plus 1.7 kg ha^{-1} plus 2.3 L ha^{-1} COC on 30 May and 4 June at Troy and Manhattan, respectively. No further weed control was necessary in 2008 due to well established stands of perennial grasses.

Nitrogen, P, and K fertilizers were applied as both pre-plant and top-dress applications to annual (Table 2.2 and 2.3) and perennial crops both site years. Starter fertilizer was applied to Miscanthus at field transplanting. Each plant was fertilized individually with 10.5 grams of Miracle-Gro® (Scotts Miracle-Gro Products, Inc., Marysville, OH) (24-8-16) plant food in a solution of 3.76 L of water. Nitrogen fertilizer was not applied to switchgrass or big bluestem at Manhattan in 2007 to minimize weed pressure. Due to low P and marginal K soil test levels at Manhattan, 151 kg P_2O_5 ha^{-1} as triple super phosphate (0-46-0) and 336 kg K_2O ha^{-1} as potash (0-60-0) were broadcast applied on 28 Mar. 2008 to all plots. In 2008, 45 kg N ha^{-1} was broadcast applied as urea (46-0-0) to perennial WS grass plots on 4 June and 17 June at Manhattan and Troy, respectively.

Annual crops were harvested after physiological maturity or before first killing frost if maturity was not reached (Table 2.2 and 2.3). Perennial WS grasses were harvested after dormancy. At Troy, perennial WS grasses were harvested on 30 Nov. 2007 and 24 Nov. 2008. Perennial WS grasses at Manhattan were harvested on 28 Nov. 2007 and 23 Nov. 2008.

Annual crops were harvested and analyzed using the same procedures at both locations in both years. A 4.6 m length of area was hand harvested from the center two rows (eight-row plots) of each plot, at an approximate stubble height of 10 cm, to minimize plot edge effects. The total wet harvested biomass mass was measured. Grain ears/heads were then counted and separated from the stover. Grain ear/head plant portions were weighed, dried in a forced-air dryer at 65º C for 48 hours, and threshed using an ALMACO (ALMACO, Nevada, IA) ECS sheller and LBD thresher for corn and sorghum, respectively. Once threshed, grain mass was obtained. At harvest, height measurements were taken of four representative plants randomly selected from each plot. Stover sub-samples from individual plots, comprised of two representative plants less grain ear/hear portion, were obtained, cut into 15-20 cm billets, weighed, dried in a forced-air dryer at 65º C for 240 hours, and weighed again to calculate DM concentration at harvest and plot DM yield. Soybean grain was harvested with a yield-monitor equipped combine at Troy, and a small-plot combine at Manhattan. Soybean stover was evenly spread back on harvested areas.

Sweet sorghum was harvested using a similar procedure as FS and corn. Once the total mass of the harvested biomass was obtained for each plot, all leaves and grain heads were removed from the stalks. Each component (i.e. leaves and grain head) was separated and weighed. Juice was extracted from the sorghum stalks using a single pass through a triple-roll sorghum mill. Sorghum juice was weighed and placed into a 3º - 5ºC cooler within 15 minutes of extraction. Sorghum juice samples were placed in long term storage at 3º C within 12 hours of extraction to minimize microbial activity and degradation of FC. Stover (stalk and leaves before pressing) and bagasse (stalk after pressing) sub-samples from individual plots, comprised of two representative plants less grain ear/hear portion, were obtained, cut into 15-20 cm billets, weighed, dried in a forced-air dryer at 65º C for 240 hours, and weighed again to calculate DM concentration before and after pressing at harvest and plot DM yield.

Fermentable carbohydrate concentration of extracted juice and bagasse, from individual plots at both locations, were analyzed and reported by Wu et al. (2008) using HPLC with a Rezex RCM-monosaccharide column (300×7.8 mm; Phenomenex, Torrence, CA, USA) and a reflective index detector (Shimadzu RID-10A, Columbia, MD, USA).

Perennial WS grasses were harvested at both locations in 2007 with a modified flail mower. A 1.2 m by 10.7 m swath through the center of the plot was harvested and weighed using a calibrated load cell and weight basket equipped on the flail mower harvester. Harvest heights were taken at four random locations near the harvested area of the plot. In 2008, a walk-behind sickle mower was used to cut a 0.91 m by 10.7 m swath through the center of each plot. Harvested biomass was then hand raked, collected, and weighed. A 225-325 g wet DM sub-sample was randomly extracted from the harvested biomass, weighed, dried in a forced-air dryer at 65º C for 240 hours, then weighed again to calculate DM concentration at harvest and plot DM yield. Harvest heights in 2007 and 2008 were approximately 5 cm and 10 cm, respectively.

Harvest moisture content (MC) of stover at harvest was calculated on a wet mass basis. Dry matter concentration for stover and grain were calculated using harvest and threshing MC, respectively. Stover yields included all above-ground harvested biomass less grain, and were standardized to zero moisture yields using the harvest MC. Grain yields were calculated from threshed grain mass; and were adjusted to zero moisture yields using the MC measured at time of threshing with a Dickey-john GAC 2000 grain analysis computer (DICKEY-john Corp., Springfield, IL). Final grain, stover, total biomass, and FC yields were extrapolated from individual plot yields.

Annual and perennial crop biomass, which was not harvested, was removed before the next growing season to simulate a complete biomass harvest. Annual crop biomass remaining in plots at Manhattan was removed on 29 Nov. 2007 and 6 Nov. 2008 with a single-row silage chopper. Chopped material was deposited in alley area between plot replications. 2007 annual crop biomass at Troy was removed on 7 Apr. 2008 with a pull-type disc-mower conditioner and round baler traveling perpendicular across the plots. Above normal winter precipitation from December 2007 through March 2008 prevented earlier biomass removal at Troy. In 2008, remaining biomass at Troy was removed on 7 November with a single-row silage chopper and deposited in alley area between plot replications. Perennial WS grass biomass was removed from plots at both locations at harvest time in 2007, with a remaining stubble height of approximately 5 cm. In 2008, perennial WS grass biomass was removed using a pull-type mower-conditioner and hay rake to cut and move the material to the alley areas between the plot replications within 10 days of harvest at both locations. Average stubble height of annual crops both years, and perennial grass in 2008 was approximately 10 cm.

Ethanol yields of grain and stover/bagasse DM were calculated using the conversion rates of 414 and 311 L Mg^{-1} DM, respectively (McAloon et al., 2000; Wang et al., 2005). Ethanol yields of FC in sweet sorghum juice were calculated assuming 1.76 kg FC L^{-1} of ethanol (Anderson et al., 1995; Putnam et al., 1991; Undersander et al., 1990). Total ethanol yields of all crops, except sweet sorghum, were comprised of the grain and/or stover. Sweet sorghum ethanol yields consisted of the grain, FC yield in extracted juice, and bagasse/leaf portions. Fermentable carbohydrate yield in juice in 2007 was found by multiplying the total extracted juice mass by percentage of FC in juice.

Population variance equality of grain, stover, total biomass, FC, harvest moisture, plant height at harvest, and ethanol yield was conducted using Hartley's test for homogeneity (Ott, 1988). Significance of main effect differences and their interactions was determined using the PROC GLIMMIX procedure (SAS Institute, 2005) with year, location, and variety as fixed effects; and replications as random effects. Mean separations were performed for the main effect treatment effects (year and/or location, and variety) if the F-tests for treatment effects were significant ($p = 0.05$).

Results

Cumulative in-season (1 April – 31 October) precipitation and GDUs for the two locations in 2007, 2008, and the 30-year normal average are illustrated in Table 2.6 (HPRCC, 2008). In-season cumulative precipitation was above normal both years at Troy and Manhattan, which normally receive 75.0 and 68.2 cm, respectively. Cumulative in-season GDUs for corn and sorghum were above normal in 2007, but below normal in 2008 at both locations. At Manhattan, multiple heavy rainfall events caused some flood damage in May and June of both study years. At Troy, mean final plant populations of corn were 84 102 and 69 039 plants ha^{-1} in 2007 and 2008 respectively; however mean corn population was 67 246 plants ha^{-1} across years at Manhattan. Sorghum mean final populations ranged from 30 843 to 69 577 plants ha^{-1} in 2007, and 113 332 to 180 039 in 2008. Increased seeding and emergence rates are responsible for increased final plant populations in 2008.

Grain Yield

A significant year x location x variety interaction (*p* = 0.05) was observed for grain yield in 2007 and 2008 at Troy and Manhattan (Table 2.7). Corn yields ranged from 8.7 to 12.0 Mg ha^{-1} with a mean of 10.1 Mg ha^{-1}, which were greater than all sorghum cultivars across locations and years (Table 2.8). Highest yield was achieved by RC in 2007 at Troy and 2008 at Manhattan. Continuous corn yielded less than RC in all site years, except at Troy in 2008 where yields of the two crops did not differ. Grain yield of CC was not different across years at individual locations. Of the sorghum cultivars, DP FS grain yields were greatest (5.3 to 7.6 Mg ha^{-1}), while those of BMR and sweet sorghum were lowest (0.7 to 4.4 Mg ha^{-1}). 'NK300' yields were greater in 2007 than 2008, but did not differ across locations in individual years. Grain yield of 'NK300' was greater than 'DKS59-09' at both locations in 2007. Brown mid-rib and sweet sorghum yields were similar throughout the study, except for *bmr* in 2007 at Manhattan, which produced yields not different than both DP FS cultivars at Manhattan in 2008. Field observations identified significant yield losses for *bmr* sorghum due to stalk lodging and grain head shattering. Due to its early maturity, bird damage to grain heads of *bmr* sorghum at Troy was observed both years. Sweet sorghum did not reach full physiological maturity before harvest or first killing freeze at either location both years, which is attributed to the long season maturity of 'M81E'. Soybean DM yields were similar across locations and years, averaging 2851 kg ha^{-1}, or 3277 kg ha^{-1} at standard (13%) MC.

Stover Yield

A significant year x variety interaction (*p* = 0.05) was observed for stover yield across locations (Table 2.7). Highest yield was produced by sweet sorghum in 2008 (Table 2.9). On 26 Aug. 2007, high winds at Troy caused severe stalk lodging and green-snap damage to sweet sorghum replication four, which decreased harvested DM yields. In 2008, significant (>95 %) sweet sorghum root lodging was observed at Troy in all replications, but did not noticeably reduce stover yields. Lodging issues with sweet sorghum were not observed in either year at Manhattan. It is suspected that higher nutrient levels at Troy (Table 2.1) are responsible for lodging. In 2007, lower sweet sorghum and 'DKS59-09' DP FS yields can be attributed to poor seed germination and reduced stands of 'DKS59-09' at Manhattan (30 843 plants ha^{-1}) and sweet sorghum across locations (37 120 plants ha^{-1}). Stover yields of sweet sorghum and PS sorghum were not different in 2007, averaging 26.6 Mg ha^{-1}. Photoperiod sensitive sorghum yield was less in 2008 (22.4 Mg ha^{-1}), than in 2007 (26.8 Mg ha^{-1}), possibly due to less cumulative in-season GDUs at both locations resulting in reduced vegetative DM accumulation. Stover yields of DP FS and *bmr* sorghum cultivars were less than PS and sweet sorghum, but equal to, or greater than, both corn rotation crops. 'DKS59-09' and *bmr* sorghum yields were greater in 2008 than 2007. Dual-purpose FS and *bmr* sorghum cultivar yields were not different in 2008, but 'NK300' DP FS achieved a greater yield in 2007. Corn yields were not different across site years, but were similar to, or less than those of sorghum. In 2007, yields of perennial WS grass cultivars were not different, but were less than annual crop yields. In 2008, yields of perennial WS grasses increased significantly over 2007 yields. Stover yields of perennial grasses in 2008 were similar to those of corn, DP FS, and *bmr* cultivars in both years.

Total Biomass Yield

A significant year x variety interaction ($p = 0.05$) was observed for the combined total biomass yield across both locations (Table 2.7). Overall, annual crops generally produced higher yields of total biomass than perennial crops (Table 2.9). The greatest yield was produced by sweet sorghum in 2008 (32.6 Mg ha^{-1}). In 2007, yields of PS and sweet sorghum were the greatest of all crops. In 2008, increased total biomass yields of sweet sorghum and 'DKS59-09' can be attributed to increased stover DM accumulation compared with 2007. Yields of DP FS and *bmr* sorghum cultivars were equal to, or less than, those of PS sorghum and both corn rotations. Corn yields, both RC and CC, were not different within individual years. Rotated corn and CC corn yields did not differ, in respect to individual crops, between years. Perennial grass yields, comprised of stover only, increased between establishment year and 2008. Switchgrass and big bluestem yields (9.2 and 7.7 Mg ha^{-1}, respectively) were less than Miscanthus (12.8 Mg ha^{-1}) in 2008. Miscanthus yields were not different than those produced by *bmr* sorghum.

Stover MC at Harvest

A significant year x location x variety interaction ($p = 0.05$) was observed for stover MC at harvest (Table 2.7). Crop type and relative maturity, along with harvest timing, influenced stover MC the greatest (Table 2.10). Sorghum cultivars had the greatest stover MC, ranging from 66% to 79%, across locations and years; however MC was similar between individual cultivars regardless of maturity length. Corn stover MC was less than sorghum, but greater than perennial WS grasses. Corn stover MC was the least at Troy in 2007 (35%), and greatest at Manhattan in 2008 (63%). Observed corn stover MC differences are explained by harvest timing. In 2007, corn at Troy was harvested much later (12 October) than corn at Manhattan in 2008 (17 September), which allowed the stover to dry down in the field longer. Perennial WS grasses generally had the lowest stover MC at harvest, ranging from 11% to 28%; however at Troy in 2008, Miscanthus stover MC was much greater (38%). Because perennial grasses were harvested after dormancy, in late November, the stover was allowed to dry for a longer period of time in the field compared to annual crops. In addition, the translocation processes within perennial grasses, along with small diameter stems, allow them to dry faster in the field compared with annuals with larger diameter stalks.

Plant Height at Harvest

A significant year x location x variety interaction ($p = 0.05$) was observed for plant height at harvest (Table 2.7). Plant height varied greatly among annual crop cultivars; however year had an influence on perennial grass height (Table 2.11). Photoperiod sensitive sorghum achieved the tallest mean plant height (418 cm) at Manhattan in 2007, and Troy both years. Height of PS sorghum at Manhattan in 2008 was lower (369 cm); but similar to the mean height of sweet sorghum across locations and years (361 cm). Dual-purpose FS heights were similar across cultivars; however differed across locations in 2007. Mean heights of DP FS cultivars ranged from 175 to 239 cm across years and locations. Corn and *bmr* sorghum heights were similar, generally ranging from 280 to 310 cm, with a mean of 291 cm; however *bmr* sorghum was shorter at Manhattan in 2007 (237 cm). In the establishment year, perennial grass heights were not different between cultivars and across locations. In 2008, plant heights increased with increased establishment, and were greatest for Miscanthus at Troy (266 cm). Height of Miscanthus will likely increase as establishment increases over the next one to three years. Big bluestem and switchgrass heights ranged from 179 to 222 cm across locations in 2008.

Sweet Sorghum FC Extraction and Yield

Sweet sorghum stover, extracted juice, and calculated FC yields were not different across locations in 2007. Average yields, extraction efficiencies, and FC concentrations are illustrated in Table 2.12. Fermentable carbohydrate extraction efficiencies and extracted juice concentration were 59.2% and 14.6%, respectively. Mean total extracted FC yield was 4.8 Mg ha^{-1}. At Troy in 2007, wind damage to the fourth replication numerically decreased juice and FC yields, but the difference was not significant. Root lodging damage in 2008 at Troy did not noticeably affect juice yields. Extracted juice samples were lost in 2008 due to refrigeration failure after harvest, which allowed the samples to warm and degrade quickly. In 2008, extracted juice (33.0 Mg ha^{-1}) and stover (31.1 Mg ha^{-1}) yields were not different across locations. In addition, measured yields in 2008 yields were not different than respective 2007 yields. Based on the limited data for 2008, it is likely that FC yields, concentrations, and extraction efficiencies were not different across locations and years.

Estimated Ethanol Yield

Ethanol yields were calculated based upon DM yields and the respective conversion rate for individual harvested plant components. A significant year x variety interaction ($p = 0.05$) was observed for the estimated ethanol yields across both study locations (Table 2.7). In general, perennial WS grass yields were lower than annual crop yields (Table 2.13). Yields of perennial WS grasses and ‘DKS59-09’ DP FS were higher in 2008 due to increased DM production. Average sweet sorghum ethanol yields (9920 L ha^{-1}) were greater than those of all annual and perennial crops in both years. Brown mid-rib sorghum yields (4591 L ha^{-1}) were the least of all annual crops in both years. Photoperiod sensitive sorghum yield decreased in 2008 due to reduced DM accumulation. Corn, sweet sorghum, *bmr*, ‘NK300’ DP FS yields did not differ between years. Mean yields of PS sorghum (8313 L ha^{-1}) in 2008 were not different than those of rotated corn (7737 L ha^{-1}) across both years. Dual-purpose FS yields were similar to RC and CC, except ‘DKS59-09’ in 2007. Rotated corn and CC yields were not different in individual years. In addition, RC and CC yields were not different between years with respect to individual crops; similar to trends observed with total biomass yields. As with total biomass yields, the highest perennial WS grass ethanol yield was achieved by Miscanthus in 2008 (3963 L ha^{-1}), which was not different than BMR sorghum either year. In 2008, switchgrass and big bluestem produced the lowest ethanol yields of all crops. Annual and perennial crop ethanol yields, except sweet sorghum, follow similar trends observed with total biomass yields, due to their direct relationship

Discussion

Yields of annual crops were similar, with respect to individual cultivars, across locations and years. Perennial crop yields were not different across locations, but increased significantly from the 2007 establishment year to 2008. Cumulative in-season precipitation was not a limiting factor for crops at either location in both years; however, excess precipitation during May and June of 2008 at Manhattan negatively impacted yields of some individual annual plots due to flood damage, and nitrogen fertilizer losses. In 2008, below normal cumulative in-season GDUs at both locations may be responsible for the decreased grain yield of ‘NK300’ DP FS and vegetative DM accumulation of PS sorghum.

Multiple factors account for yield component differences among individual crops. In 2007, poor emergence and low final stands of ‘DKS59-09’ DP FS were responsible for reduced stover and total biomass accumulation; however grain yields were not affected. Sweet sorghum grain yields were low due to characteristically low grain yield potential, as well as inability to reach full physiological maturity across all four site years before harvest or first killing frost.

Corn achieved the highest grain yields of all crops. Grain yields of RC were greater than CC at Troy in 2007, and Manhattan both years, which is supported by Maloney et al. (1999). Factors influencing these yield differences include reduced insect and disease pressure, reduced N immobilization, and changes in soil texture due to the addition of soybeans into the crop rotation (Blackmer and Green, 1995; Boosalis and Doupnik, 1976; Karlen et al., 1994). Dual-purpose FS grain yields were generally greater than other sorghum cultivars throughout the study, but less than corn. Brown mid-rib sorghum grain yields were negatively impacted by grain head shattering, stalk lodging and bird damage.

Stover and total biomass yields of annual crops were generally greater then perennial crops across all site years. Sweet and PS sorghum cultivars accumulated the greatest amount of stover and total biomass DM; however reduced PS sorghum yields in 2008 were similar to those of corn and DP FS. Stover yields of both DP FS cultivars were generally greater than corn, but total biomass yields were not different. These data show that the grain harvest index of corn was greater than that of the DP FS. Greater stover yields of DP FS, compared with corn, made up for the decreased grain production, therefore total biomass yields of DP FS and corn were similar. Significant root lodging of sweet sorghum was observed both years at Troy, but not Manhattan; likely due to higher nutrient levels at Troy. Lodging increased harvest difficulty, but did not seem to affect overall DM or FC yields. Reduced N management and lower seeding rates may be critical for sweet and *bmr* sorghum cultivars to minimize lodging issues (Bean et al., 2003). Stover yields of perennial WS grasses increased significantly from 2007 to 2008. Perennial grass yields in 2008 were equal to, or less than, those of the lowest yielding annual crops. Stover DM yields of perennial grasses will likely increase over the next one to three years as stands become fully established, and N fertilizer rates are increased accordingly (Christian et al., 2008; Sanderson and Adler, 2008). It is questionable whether or not stover and total biomass yields of switchgrass or big bluestem will reach those of Miscanthus, or high yielding sorghum cultivars.

Stover MC at harvest was greatest for sorghum, regardless of cultivar. Corn stover MC at harvest was less than sorghum, and similar to values reported by Pordesimo et al. (2004). Sorghum stover will retain high MC levels in the stalks late into the season until killed by freeze, when it will slowly dry to reduced MC levels. Late season harvesting allowed perennial grass biomass to be harvested at much lower MC than annual crop stover. Moisture levels of biomass are critical to determine proper harvest and storage methods for quality preservation. In addition, high energy inputs are required to remove moisture from biomass, therefore as the MC of harvested biomass increases, the efficiency of the energy conversion system decreases due to increased drying requirements and costs.

Sweet sorghum juice and FC yields were not different across locations in 2007. Although 2008 sweet sorghum FC data were not analyzed, juice and stover yields between the four site years were not different; suggesting that FC yields would be similar. On average, 59.2% of the total FC in the sweet sorghum stover was extracted by the triple-roll mill, thus leaving over 40% remaining in the stalks. Extracted FC yields are similar to those reported by Putnam et al. (1991). Alternative pressing processes could likely achieve 75%, or greater, FC extraction rates. Sweet sorghum harvest must be managed so that extracted juice is processed, or put into proper storage, in a timely manner. Failure to do so will result in rapid juice and FC degradation, as seen with juice samples in 2008.

Total estimated ethanol yields followed similar trends as total biomass yields. The conversion rates for grain and FC are generally accepted industry standards with current process technology. Ethanol conversion yields for lignocellulosic biomass (i.e. stover) are intermediate levels of those reported (McAloon et al., 2000). Ethanol yields of stover from cellulosic ethanol conversion processes will vary based upon the lignin contents of individual crop cultivars. Crops with low lignin content, such as *bmr* sorghum, will have higher ethanol conversion ratios per unit of biomass compared to cultivars with high lignin content, such as PS sorghum. Future research is needed to determine ethanol conversion rates of individual crop biomass. In this study, the complete utilization of sweet sorghum for ethanol production was observed to achieve the greatest ethanol yields of all crops in all four site years. Ethanol yields of DP FS, PS sorghum, RC and CC were similar. Perennial grasses and BMR sorghum produced the lowest ethanol yields, however it is likely total biomass and ethanol yields of perennial grasses in this study will continue to increase in the next one to three years with increasing yields.

Results of the study suggest that RC remains the best crop choice for grain starch based ethanol conversion processes. Although water stress was not a limiting factor in this study, in regions where water is limited, sorghum has the potential to produce equal, or greater, yields than corn. For cellulosic ethanol conversion processes, sweet sorghum and PS sorghum produce the greatest stover yields, with little to no grain. Lack of grain allows the crops to be harvested without the need of grain separation since different ethanol conversion processes are used for the individual plant components. Ethanol production can be maximized by the complete utilization of all harvestable sweet sorghum components. Reduced N fertility needs (Anderson et al., 1995) and low energy inputs required for FC ethanol conversion processes will likely allow sweet sorghum to achieve higher energy efficiencies than corn or other sorghum cultivars. Biomass and ethanol production from perennial grass crops before full stand establishment will be minimal, and may take two to five years to reach harvestable levels. Research has shown Miscanthus can achieve biomass and ethanol yields similar to those of high-tonnage annual crops. Biomass production of switchgrass and big bluestem will likely remain less than Miscanthus or annual crops, although reduced energy input requirements may allow them to be selected as viable biofuel crops in marginal production areas. Final crop selection must be determined after evaluating the production region, ethanol conversion process in use, energy efficiency, and economic viability of the system. The results of this study provide data for biomass and ethanol yield estimation of non-traditional annual and perennial crops, relative to corn, which can be utilized by agricultural and energy producers for management and economic forecasting of biofuel cropping systems.

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Chapter 2 – Tables

Table 2.1. Pre-plant soil test results in 2007 at Troy and Manhattan.

Location	Depth	pH	P	K	NH_4-N	NO_3-N	OM
	cm		ppm	ppm	ppm	ppm	%
Troy†	0-15	6.9	83	331	54	40	3.2
	15-30	6.3	47	173	12	22	2.7
Manhattan	0-15	6.6	15	195	6.8	57	2.5
	15-30	6.7	6	121	2.7	8	2.3

† Anhydrous ammonia (82-0-0) applied in fall prior to soil sampling.

Table 2.2. Planting, nitrogen fertilization, and harvest dates and seeding and fertilizer rates of annual crops in 2007 at Troy and Manhattan.

Location	Variety	Planting Date	Target Seeding Rate	Nitrogen Rate†	Nitrogen Application Date	Harvest Date
Troy			seeds ha^{-1}	kg N ha^{-1}		
	PS 1990CA	16 May	143 000	180	Nov. 2006	27 Oct.
	Sweet M81E	16 May	143 000	180	Nov. 2006	27 Oct.
	DP FS NK300	16 May	143 000	180	Nov. 2006	12 Oct.
	DP FS DKS59-09	16 May	143 000	180	Nov. 2006	12 Oct.
	BMR GW8528	16 May	143 000	180	Nov. 2006	27 Oct.
	Rotated Corn 33K40	19 Apr.	68 000	180	Nov. 2006	12 Oct.
	Continuous Corn 33K40	19 Apr.	68 000	180	Nov. 2006	12 Oct.
	Soybean 3824RR	16 May	250 000	180	Nov. 2006	2 Oct.
Manhattan						
	PS 1990CA	21 May	143 000	168	22 May	23 Oct.
	Sweet M81E	21 May	143 000	168	22 May	25 Oct.
	DP FS NK300	21 May	143 000	168	22 May	23 Oct.
	DP FS DKS59-09	21 May	143 000	168	22 May	11 Oct.
	BMR GW8528	21 May	143 000	168	22 May	23 Oct.
	Rotated Corn 33K40	14 May	68 000	168	22 May	29 Sept.
	Continuous Corn 33K40	14 May	68 000	168	22 May	29 Sept.
	Soybeans KSU3406RR	14 May	250 000	-	-	2 Nov.

†Nitrogen fertilizer applied as 82-0-0 at Troy and as 46-0-0 at Manhattan.

Table 2.3. Planting, nitrogen fertilization, and harvest dates and seeding and fertilizer rates of annual crops in 2008 at Troy and Manhattan.

Location	Variety	Planting Date	Target Seeding Rate	Nitrogen Rate†	Nitrogen Application Date	Harvest Date
Troy			seeds ha^{-1}	kg N ha^{-1}		
	PS 1990CA	30 May	191 000	180	4 June	27 Oct.
	Sweet M81E	30 May	191 000	180	4 June	10 Oct.
	DP FS NK300	30 May	191 000	180	4 June	27 Oct.
	DP FS DKS59-09	30 May	191 000	180	4 June	27 Oct.
	BMR GW8528	30 May	191 000	180	4 June	26 Sept.
	Rotated Corn 33K44	23 Apr.	68 000	180	4 June	26 Sept.
	Continuous Corn 33K44	23 Apr.	68 000	180	4 June	26 Sept.
	Soybeans KSU3406RR	30 May	296 000	-	-	12 Oct.
Manhattan						
	PS 1990CA	21 May	191 000	180	17 June	20 Oct.
	Sweet M81E	21 May	191 000	180	17 June	3 Oct.
	DP FS NK300	21 May	191 000	180	17 June	20 Oct.
	DP FS DKS59-09	21 May	191 000	180	17 June	20 Oct.
	BMR GW8528	21 May	191 000	180	17 June	17 Sept.
	Rotated Corn 33K44	22 Apr.	68 000	180	17 June	17 Sept.
	Continuous Corn 33K44	22 Apr.	68 000	180	17 June	17 Sept.
	Soybeans KSU3406RR	21 May	296 000	-	-	18 Nov.

†Nitrogen fertilizer applied as 46-0-0 at both locations

Table 2.4. PRE- and POST-emergence herbicide application information for annual crops at Troy and Manhattan in 2007.

Location	Variety	PRE-herbicide and rate#	POST-herbicide and rate	POST-herb. appl. date
		kg a.i. ha^{-1}	kg a.i. ha^{-1}	
Troy†				
	PS 1990CA	0.47 glufosinate§ + 1.6 S-metolachlor¶	-	-
	Sweet M81E	0.47 glufosinate + 1.6 S-metolachlor	-	-
	DP NK300	0.47 glufosinate + 1.6 S-metolachlor	-	-
	DP DKS59-09	0.47 glufosinate + 1.6 S-metolachlor	-	-
	BMR GW8528	0.47 glufosinate + 1.6 S-metolachlor	-	-
	Rotated corn	-	0.47 glufosinate + 1.6 S-metolachlor	19 May
	Cont. Corn	-	0.47 glufosinate + 1.6 S-metolachlor	19 May
	Soybeans	0.47 glufosinate + 1.6 S-metolachlor	1.1 glyphosate	7 July
Manhattan‡				
	PS 1990CA	1.8 atrazine + 1.41 S-metolachlor	-	-
	Sweet M81E	1.8 atrazine + 1.41 S-metolachlor	-	-
	DP NK300	1.8 atrazine + 1.41 S-metolachlor	-	-
	DP DKS59-09	1.8 atrazine + 1.41 S-metolachlor	-	-
	BMR GW8528	1.8 atrazine + 1.41 S-metolachlor	-	-
	Rotated corn	-	1.8 atrazine + 1.4 S-metolachlor	25 May
			0.47 glufosinate	21 June
	Cont. Corn	-	1.8 atrazine + 1.4 S-metolachlor	25 May
			0.47 glufosinate	21 June
	Soybeans	1.8 atrazine + 1.41 S-metolachlor	1.1 glyphosate	15 June
			1.1 glyphosate	12 July

†Atrazine [2-chloro-4-(ethylamino-6-(isopropylamino)-s-triazine] applied to all plots at Troy in fall 2006 at rate of 1.7 kg ha^{-1}.

‡Glyphosate [N-(phosphonomethyl)glycine] applied at Manhattan on 14 May at the rate of 1.1 kg ha^{-1} as pre-plant burndown.

§Glufosinate [2-amino-4-(hydroxymethylphosphinyl)]

¶S-metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl] acetamide]

PRE-emergence herbicides applied at planting time.

Table 2.5. PRE- and POST-emergence herbicide application information for annual crops at Troy and Manhattan in 2008.

Location	Cultivar	PRE-herbicide and rate[††]	POST-herbicide and rate	POST-herb. application date
Troy		kg a.i. ha^{-1}	kg a.i. ha^{-1}	
	PS 1990CA	1.8 atrazine[†] + 1.4 S-metolachlor[¶]+ 1.1 glyphosate[‡]	1.12 atrazine	17 June
	Sweet M81E	1.8 atrazine + 1.4 S-metolachlor+ 1.1 glyphosate	1.12 atrazine	17 June
	DP NK300	1.8 atrazine + 1.4 S-metolachlor+ 1.1 glyphosate	1.12 atrazine	17 June
	DP DKS59-09	1.8 atrazine + 1.4 S-metolachlor+ 1.1 glyphosate	1.12 atrazine	17 June
	BMR GW8528	1.8 atrazine + 1.4 S-metolachlor+ 1.1 glyphosate	1.12 atrazine	17 June
	Rotated corn	1.9 S-metolachlor + 0.2 mesotrione[§]+ 0.7 atrazine	1.1 glyphosate	30 May
	Cont. Corn	1.9 S-metolachlor + 0.2 mesotrione + 0.7 atrazine	1.1 glyphosate	30 May
	Soybeans	1.1 glyphosate	1.1 glyphosate	17 June, 17 July
Manhattan				
	PS 1990CA	1.8 atrazine + 1.4 S-metolachlor+ 1.1 glyphosate	0.42 diglycolamine salt[#] + 1.1 atrazine	23 June
	Sweet M81E	1.8 atrazine + 1.4 S-metolachlor+ 1.1 glyphosate	0.42 diglycolamine salt + 1.1 atrazine	23 June
	DP NK300	1.8 atrazine + 1.4 S-metolachlor+ 1.1 glyphosate	0.42 diglycolamine salt + 1.1 atrazine	23 June
	DP DKS59-09	1.8 atrazine + 1.4 S-metolachlor+ 1.1 glyphosate	0.42 diglycolamine salt + 1.1 atrazine	23 June
	BMR GW8528	1.8 atrazine + 1.4 S-metolachlor+ 1.1 glyphosate	0.42 diglycolamine salt + 1.1 atrazine	23 June
	Rotated corn	1.9 S-metolachlor + 0.2 mesotrione + 0.7 atrazine	-	-
	Cont. Corn	1.9 S-metolachlor + 0.2 mesotrione + 0.7 atrazine	-	-
	Soybeans	1.1 glyphosate	1.1 glyphosate	14 June, 14 July

† Atrazine [2-chloro-4-(ethylamino-6-(isopropylamino)-s-triazine]

‡ Glyphosate [N-(phosphonomethyl)glycine]

§ Mesotrione [2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione]

¶ S-metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl] acetamide]

Diglycolamine salt [3,6-dichloro-o-anisic acid] applied lay-by with hooded sprayer.

†† PRE- emergence herbicides applied at planting time.

Table 2.6. In-season cumulative growing degree units and precipitation.

Location/ Crop	Growing Degree Units†‡			Precipitation†		
	2007	2008	Normal	2007	2008	Normal
		GDUs			cm	
Troy				80.2	86.8	75.0
Corn	3950	3498	3648			
Sorghum	4127	3563	3724			
Manhattan				88.3	93.6	68.2
Corn	4240	3601	3866			
Sorghum	4619	3806	4028			

† Growing season considered 1 April - 31 October of each year. GDUs and precipitation data from High Plains Regional Climate Center (2008).

‡ Base temperature of 10º C used for GDU calculation.

Table 2.7. Analysis of variance results for grain yield, stover yield, total biomass yield, ethanol yield, stover harvest moisture, and stalk height at harvest.

Effect	Grain Yield	Stover Yield	Total Biomass Yield	Ethanol Yield	Stover Harvest Moisture	Harvest Stalk Height
				Pr > F		
Year	0.0038	0.0010	0.0044	0.0159	0.0122	0.0002
Location	0.3425	0.1356	0.1230	0.1799	0.2953	0.0034
Year x Location	0.1151	0.8627	0.5926	0.4088	0.0096	0.1299
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Year x Cultivar	0.0049	<0.0001*	<0.0001*	<0.0001*	<0.0001	<0.0001
Location x Cultivar	0.0007	0.3059	0.6456	0.6640	<0.0001*	<0.0001*
Year x Location x Cultivar	0.0058*	0.2096	0.2826	0.2735	0.0130	0.0009

* Significant at the *p* = 0.05 probability level.

Table 2.8. Grain dry matter yields of annual crops at Troy and Manhattan in 2007 and 2008.

Cultivar	Grain Yield							
	Troy				Manhattan			
	2007		2008		2007		2008	
	Mg ha^{-1}							
Rotated Corn	12.0	a†	10.0	bc	10.0	bc	11.0	ab
Continuous Corn	10.2	bc	10.0	bc	8.7	de	9.1	cd
DP FS NK300	7.5	f	5.9	gh	7.6	ef	5.0	hi
DP FS DKS59-09	6.3	g	6.2	g	5.6	gh	5.3	hij
BMR GW8528	2.5	jk	1.5	jkl	4.4	i	2.7	j
Sweet Sorg. M81E	2.1	jk	0.7	l	1.5	kl	2.1	jk

† Mean yields across locations and years followed by the same letter are not different, $p = 0.05$.

Table 2.9. Stover and total biomass dry matter yields in 2007 and 2008 across two locations in Kansas.

Cultivar	Stover				Total Biomass			
	2007		2008		2007		2008	
	Mg ha^{-1}							
PS 1990CA	26.8	b†	22.4	c	26.8	b	22.4	c
Sweet Sorg. M81E	26.4	b	31.1	a	28.2	b	32.6	a
DP FS NK300	13.1	de	14.1	d	20.7	cd	19.6	cd
DP FS DKS59-09	9.8	fg	13.9	d	15.8	e	19.6	cd
BMR GW8528	9.4	fg	12.7	de	12.9	f	14.8	fe
Rotated Corn	11.1	ef	10.1	fg	22.1	cd	20.6	cd
Continuous Corn	10.8	ef	9.5	fg	20.3	cd	19.0	d
Kaw Big bluestem	4.4	h‡	7.7	g	4.4	h	7.7	g
Kanlow Switchgrass	4.1	h	9.2	fg	4.1	h	9.2	g
Miscanthus	3.3	h	12.8	de	3.3	h	12.8	f

†Mean yields of a biomass component (i.e. stover) across years followed by the same letter are not different, $p = 0.05$.

‡ 2007 was establishment year for all perennial grass cultivars.

Table 2.10. Harvest moisture content of annual and perennial crops at Troy and Manhattan in 2007 and 2008.

	Troy		Manhattan	
Cultivar	2007	2008	2007	2008
	%			
PS 1990CA	72 bcde[†]	72 bcdef	70 defg	66 fgh
Sweet Sorg. M81E	75 abcde	71 defg	73 bcde	74 abcde
DP FS NK300	77 abc	75 abcd	73 abcde	69 efg
DP FS DKS59-09	79 a	75 abcde	78 ab	71 defg
BMR GW8528	73 abcde	74 abcde	71 cdef	72 bcde
Rotated Corn	35 l	55 jk	58 ij	65 gh
Continuous Corn	35 l	57 ij	49 k	61 hi
Kaw Big bluestem	11 q	17 nopq	22 mn	11 q
Kanlow Switchgrass	15 opq	21 no	20 nop	14 pq
Miscanthus	20 nop	38 l	19 nop	28 m

† Mean moisture contents across locations and years followed by the same letter are not different, $p = 0.05$.

Table 2.11. Plant height at harvest of annual and perennial crops at Troy and Manhattan in 2007 and 2008.

	Troy				Manhattan			
Cultivar	2007		2008		2007		2008	
	cm							
PS 1990CA	433	a†	411	ab	411	ab	369	cd
Sweet Sorg. M81E	357	de	339	e	355	de	393	bc
DP FS NK300	239	k	216	klmn	192	opq	210	mnop
DP FS DKS59-09	214	lmno	203	mnop	175	q	188	pq
BMR GW8528	280	ij	280	hij	237	lk	287	ghij
Rotated Corn	310	fg	280	hij	311	f	293	fghi
Continuous Corn	304	fgh	281	hij	300	fghi	280	hij
Kaw Big bluestem	137	r	196	nopq	136	r	179	q
Kanlow Switchgrass	135	r	222	klm	125	r	180	q
Miscanthus	120	r	266	j	117	r	239	k

† Mean heights across locations and year followed by the same letter are not different, $p = 0.05$.

Table 2.12. M81E sweet sorghum juice and fermentable carbohydrate (FC) yields in 2007 across two locations in Kansas.

Extracted Juice Yield	Juice FC‡ concentration	Extracted FC yield	FC§ extraction efficiency	Total FC in stover yield	FC‡¶ concentration in stover	Dry stover yield
Mg ha^{-1}	%	Mg ha^{-1}	%	Mg ha^{-1}	%	Mg ha^{-1}
32.8	14.6	4.8	59.2	8.1	30.7	26.4

‡ Juice and stover FC analysis from Wu et al., 2008.
§ Percentage of FC extracted with single pass through triple-roll sorghum mill.
¶ Percentage of FC in stover dry matter.

Table 2.13. Estimated total ethanol yields by variety across locations in 2007 and 2008.

Cultivar	Ethanol 2007		Ethanol 2008	
	L ha^{-1}			
PS 1990CA‡	8313	b†	6961	d
Sweet Sorg. M81E§	9656	a	10184	a
DP FS NK300¶	7203	cd	6654	d
DP FS DKS59-09¶	5514	e	6694	d
BMR GW8528¶	4356	f	4825	ef
Rotated Corn¶	7997	bc	7477	bcd
Continuous Corn¶	7275	cd	6899	d
Kaw Big bluestem‡	1382	h	2404	g
Kanlow Switchgrass‡	1288	h	2851	g
Miscanthus‡	1035	h	3963	f

† Mean total ethanol yields across years followed by the same letter are not different, $p = 0.05$.
‡ Ethanol yields from stover components only.
§ Ethanol yields from grain, bagasse and leaves, and extracted fermentable carbohydrates combined.
¶ Ethanol yields from stover and grain components combined.

CHAPTER 3 – Nutrient Concentrations and Removal Rates of Annual and Perennial Biofuel Crops

Abstract

The concentration and total removal of nutrients in grain and stover are important factors which must be considered when selecting crops for renewable fuel production. A study was conducted to determine the mineral nutrient (N, P, and K) composition of grain and stover, as well as the total nutrient removal of grain, stover, and total biomass of annual and perennial C4 crops in northeast Kansas in 2007 and 2008 based on biomass yields. Extracted sweet sorghum juice was analyzed for nutrient concentration and total removal as well. Selected crops included corn (*Zea mays* L.) grown continuously (CC) and rotated (RC) with soybean [*Glycine max* (L.) Merr.], five sorghum [*Sorghum bicolor* (L.) Moench] cultivars; brown mid-rib (*bmr*), photoperiod sensitive (PS), sweet, and two dual-purpose (DP) forage varieties, rotated with soybean, as well as three perennial warm-season (WS) grasses; switchgrass (*Panicum virgatum* L.), big bluestem (*Andropogon gerardii* Vitman), and Miscanthus (*Miscanthus x giganteus*). Annual crops were harvested after physiological maturity, or before first killing freeze, while perennial grasses were harvested after dormancy. Sweet sorghum juices were extracted in-field at harvest. Annual crop yields, and total nutrient removal, were greater than those observed for perennial grasses. Yields of annual crops varied among cultivar selection, but were similar between locations and years. Perennial grass stover nutrient concentrations were greatest in the establishment year (2007). Perennial grass yields increased significantly from 2007 to 2008; however nutrient removal was not affected by the yield increase. Grain nutrient removal was greatest for corn even though nutrient concentrations were less than, or equal to, those found in sorghum grain. Total nutrient removal was most influenced by biomass yield; however P accumulation was greater at Troy than Manhattan due to differences in soil P levels. Total K removal was highest for the PS, sweet, and DP forage sorghum cultivars. These results indicate that annual crops can produce greater quantities of biomass compared with perennial grasses; however high biomass removal require increased nutrient management and fertilizer inputs for annual crops.

Introduction

Increasing demand for biofuel crop production to support the developing renewable fuel industry, within the United States, will require the removal of high amounts of biomass from cropland. The combination of grain and stover harvesting will result in increased removal of accumulated mineral nutrients, potentially depleting levels within the soil over time. Commercial fertilizers generally require high energy inputs to extract, transport, and/or produce, which will have a significant effect on the overall energy efficiency of a renewable fuel production system. Nutrient accumulation in grain and stover can negatively affect ethanol conversion processes; as well as other renewable energy processes such as combustion for steam and electricity generation. Nutrient concentrations and removal amounts by harvested biomass are needed to determine fertilizer recommendations, composition, energy conversion process suitability, and overall economic viability of biofuel cropping systems. Plants require, and accumulate, macronutrients [nitrogen (N), phosphorus (P), and potassium (K)] at higher levels than other mineral nutrients.

Harvesting perennial WS grass crops after dormancy has been shown to significantly reduce nutrient concentration and removal (Boehmel et al., 2008; Clifton-Brown et al., 2007; Himken et al., 1997; McLaughlin et al., 1999). As dormancy approaches in the fall, perennial

WS grasses translocate minerals and carbohydrates into the crown and rhizome components for over-wintering and spring regrowth (Sanderson and Alder, 2008). This physiological process reduces fertilizer requirements, increases biomass energy conversion suitability, and energy system efficiencies of perennial WS grasses compared with annual crops.

Nitrogen is generally required in the greatest amount, relative to other nutrients, for plant growth and development of grass crops. Additionally, N is the most energy intensive fertilizer to produce; therefore it is a major energy and economic input cost for grass crops in production systems (Boerjesson, 1996). Nitrogen accumulation in grain and stover can be undesirable for energy conversion processes. During direct combustion processes, N in lignocellulosic (LC) biomass emits compounds contributing to air pollution and corrodes boiler systems (Lewandowski and Kicherer, 1997). Nitrogen accumulation in corn and sorghum grain is directly associated with protein accumulation, however high starch content in grain is more desirable to obtain maximum ethanol conversion efficiencies and overall production. Wu et al. (2008) alluded to inversely related protein and starch accumulation in sorghum grain; suggesting that longer grain filling periods increase starch accumulation while decreasing N and protein content. Nitrogen removal by corn grain and stover have been reported to be lower in CC monocultures compared with corn rotated with soybean due to general lower biomass yields of CC (Maloney et al., 1999). Forage sorghum, although productive at relatively low input levels, generally shows a positive yield response to N and is considered to have N concentrations and removal similar to those of corn silage. Sweet sorghum has been reported to achieve higher N use efficiencies than other annual grass crops (Anderson et al., 1995). Bean et al. (2008) supported this and found that sweet sorghum removed 38% less N than grain or FS cultivars even though dry matter (DM) yields were similar. Due to the N translocation abilities of perennial WS grasses, N concentration in the aboveground biomass is significantly less after dormancy. Nitrogen removal by Miscanthus and switchgrass have been found to be reduced by 21% to 46% when harvested after dormancy in the fall, or at later dates (Clifton-Brown et al., 2007; Himken et al., 1997; McLaughlin et al., 1999). Clark (1977) reported that 58% of N accumulated in big bluestem was translocated into the stem bases during senescence in the fall.

Phosphorus accumulation in biomass is not widely reported to cause ethanol conversion issues, but can be a negative factor in thermochemical or direct combustion energy conversion processes. Grain and/or stover removal, especially at high rates like those for silage or biofuel production, requires organic or inorganic P fertilizer amendments to be applied to prevent plant deficiency symptoms and maintain full yield potential. Phosphorus uptake in plants is highly dependent upon soil P and moisture availability; and as plant age and moisture stress increase, P accumulation in plants decreases (Payne et al., 1995). Research by Riedell et al. (1998) supported this and found P concentration in CC stover to be higher than RC stover under low input fertilizer management rates due to CC plots having higher soil P values than RC. Like N, P removal by FS is similar to that of corn. McCollum and Bean (2003) found total P removal of corn, *bmr* , and non-*bmr* FS cultivars to be similar (~42 kg ha^{-1}) when harvested for silage; however PS sorghum cultivars removed significantly higher (58 kg ha^{-1}) amounts due to overall greater biomass yields. Sweet sorghum P removal is similar to other sorghum cultivars. Undersander et al. (1990) stated that sweet sorghum producing yields of 11-16 Mg ha^{-1} will remove approximately 45 kg P ha^{-1}. Although nutrient concentration data for sweet sorghum juice is limited, Fenzhou (1989) found P concentrations across multiple cultivars to be very low, ranging from 35-110 ppm. Phosphorus is a plant mobile nutrient which is translocated out of aboveground perennial WS grass biomass as the plant approaches dormancy. Stover P concentrations and removal by perennial WS grass cultivars have been reported to decrease by 36% - 50% when harvest is delayed to post-dormancy (Clifton-Brown et al., 2007; Himken et al., 1997). Typical biomass P concentrations and total removal, when utilizing a post-dormancy harvest, range from 900-1700 ppm and 8 -15 kg ha^{-1}, respectively (Clifton-Brown et al., 2007; Cassida et al., 2005).

Accumulation of K in biomass is undesirable for direct combustion energy conversion processes due to corrosion and boiler fouling issues. For ethanol production processes, K accumulation in the non-fermentable lignin portion of stover may cause problems if used for direct combustion processes. Much of the soil in the semi-arid (<76 cm annual rainfall) Great Plains region contains high K levels; therefore K fertilization for most grain cropping systems is currently not required. Potassium removal by plants is most affected by plant available K in soil, soil moisture, soil temperature, and tillage management across different locations. Total plant K uptake is generally less than N, but greater than P. Leikam et al. (2003) reported K removal by corn and sorghum grain and total biomass to be 4.6 and 10.2 kg Mg^{-1} DM, respectively. Buxton et al. (1999) suggested that K concentrations in sorghum increased when plants were water stressed due to K accumulating at higher rates than DM. The study also reported that increasing N fertility did not affect average sorghum stover K concentrations (13,775 ppm). Sweet sorghum accumulates similar K levels as other FS cultivars, with DM yields of 11-16 Mg ha^{-1} removing about 200 kg K ha^{-1}, however most K remains in the structural carbohydrates of the plant (Undersander et al., 1990). Fenzhou (1989) reported extracted sweet sorghum juice from multiple varieties to have K concentrations ranging from 904- 3087 ppm. Potassium concentrations in perennial WS grass stover can vary greatly from year to year due to rain leaching K from plant tissue (Sander, 1997). Translocation processes within perennial WS grass crops move K out of stover as the plant approaches dormancy, similar to N and P; therefore harvest timing will affect the stover K concentration as well. Clifton-Brown et al. (2007) reported that Miscanthus K removal decreased from 69 to 8 kg ha^{-1} when harvest was delayed from fall to early spring of the following year. Potassium concentrations of several switchgrass cultivars, grown at multiple locations, were found to range from 6200 – 15,800 ppm. Like Miscanthus, K removal of switchgrass and big bluestem can be significantly reduced by harvesting after an over-wintering period (Adler et al., 2006).

The objectives of this study were to evaluate yields and macro-nutrient concentrations of grain, stover, and extracted sweet sorghum juice to determine N, P, and K removal by annual and perennial C4 biofuel crops grown under similar soil classification and weather conditions at two locations in northeast KS.

Materials and Methods

Research was conducted in 2007 and 2008 at two dryland locations in northeast Kansas; Troy (39º77'N, 95º12'W) and the Kansas State University (KSU) Agronomy Research Farm at Manhattan (39º11'N, 96º35'W). Soil types included a Kennebec silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludolls) at Troy, and an Ivan, Kennebec, and Kahola silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludolls) at Manhattan. Soil samples were taken at the 0-15 cm surface and 15-30 cm depth at both locations before planting in April 2007 to analyze organic matter (OM), pH, P, K, and N [ammonia (NH_3) and nitrate (NO_3)] (Table 3.1). Samples at each location were composed of 15 individual soil cores representatively taken across each site area. Phosphorus levels at Manhattan at the 0 – 15 cm and 15 – 30 cm soil depths were 15 and 6 parts per million (ppm), respectively. Although the P levels were below the critical soil test level (20 ppm), they were not addressed for the 2007 growing season. All crops were no-till planted at each location. Cumulative in-season growing degree units (GDUs), precipitation amounts for both site years, and 30-year normals, were based on individual location weather station data (High Plains Regional Climate Center, 2008). Growing degree units were calculated using maximum temperatures (T_{max}) of 29.4º C and 38º C for corn and sorghum, respectively. Minimum (T_{min}) and base (T_{base}) temperatures of 10º C were used for both crops.

The study was designed as a randomized complete block experiment with four replications at each location. Individual plot size was 6.1 m wide by 10.7 m long. The corn hybrids grown in 2007 and 2008 were Pioneer '33K40' (Bt) and Pioneer '33K44' (Bt), respectively; both of the same parent family with relative maturity of 114 days (Pioneer Hi-Bred International, Johnston, IA). Sorghum cultivars include: Crosbyton 'GW8528' (Crosbyton Seed Co., Crosbyton, TX) *bmr* FS, Land O'Lakes 'DKS59-09' (Land O'Lakes, St. Paul, MN) DP FS, Mississippi State University 'M81E' sweet sorghum, Sorghum Partners 'NK300' (Sorghum Partners, Inc., New Deal, TX) DP FS, and Sorghum Partners '1990CA' PS sorghum. Soybean varieties planted for rotational purposes included Garst '3824RR' (Garst Seed Co., Slater, IA) at Troy in 2007 and KSU Foundation 'KS3406RR' (Kansas State Univ., Manhattan, KS) at Troy in 2008 and Manhattan both study years. Perennial grass species included; 'Kanlow' switchgrass, 'Kaw' big bluestem, and Miscanthus.

Annual crops were planted in April and May of each year with a no-till row crop planter on 76.2 cm row spacing (Tables 3.2. and 3.3). Soybean was the previous crop for all annuals in both years, except for CC in 2008 which was planted into the 2007 CC residue.

Perennial WS grasses were established in May and June of 2007 into soybean residue. Switchgrass and big bluestem were seeded on 16 May at Troy and 14 May at Manhattan with a Truax FLXII-88 (Truax Company, Inc., New Hope, MN) grass drill on 20.3 cm row spacing.

Grasses were seeded at a depth of 0.6 to 1.3 cm. Bulk seeding rates were 7.9 kg ha^{-1} (4.0 kg ha^{-1} pure live seed (pls) for the switchgrass and 20.2 kg ha^{-1} (6.3 kg ha^{-1} pls) for the big bluestem. Miscanthus was planted on 11 June and 12 June at Manhattan and Troy, respectively. Individual plants were hand transplanted from the greenhouse to field plots at a population of 6148 plants ha^{-1} using a 1.2 m by 1.0 m grid spacing. Switchgrass in the first replication at the Manhattan site was replanted on 2 May 2008 due to very poor establishment in 2007. Planting methods were the same as in 2007.

Weed control in all crops was accomplished by herbicides and hand weeding as necessary to minimize weed pressure throughout the growing season both years (Chapter 2, Tables 2.4 and 2.5)

Nitrogen, P, and K fertilizers were applied as both pre-plant and top-dress applications to annual (Table 3.2 and 3.3) and perennial crops both site years. Starter fertilizer was applied to Miscanthus at field transplanting. Each plant was fertilized individually with 10.5 grams of Miracle-Gro® (Scotts Miracle-Gro Products, Inc, Marysville, OH) 24-8-16 plant food in a solution of 3.76 L of water. Nitrogen fertilizer was not applied to switchgrass or big bluestem at Manhattan in 2007 to minimize weed pressure. Due to low P and marginal K soil test levels at Manhattan, 151 kg P_2O_5 ha^{-1} as triple super phosphate (0-46-0) and 336 kg K_2O ha^{-1} as potash (0-60-0) were broadcast applied on 28 March 2008 to all plots. In 2008, 45 kg N ha^{-1} was broadcast applied as urea (46-0-0) to perennial WS grass plots on 4 June and 17 June at Manhattan and Troy, respectively.

Annual crops were harvested after physiological maturity or before first killing frost if maturity was not reached (Table 3.2 and 3.3). Complete harvesting procedures are described in Chapter 2. A 4.6 m length of area was hand harvested from the center two rows (eight-row plots) of each plot, at an approximate stubble height of 10 cm, to minimize plot edge effects. Harvested grain and stover were separated and dried in a forced-air dryer at 65° C for 48 and 240 hours, respectively. Sub-samples were randomly extracted from the harvested biomass and retained to determine dry matter and nutrient concentrations. Sweet sorghum was harvested using a similar procedure as other sorghum cultivars and corn. After harvest, all leaves and grain heads were separated from the sweet sorghum stalks; juices were then extracted from the stalks using a single pass through a triple-roll sorghum mill. Extracted juices were placed in cool storage to preserve quality. Soybean was harvested with a yield-monitor equipped combine at Troy, and a small-plot combine at Manhattan.

Perennial WS grasses were harvested after dormancy. At Troy, perennial WS grasses were harvested on 30 November 2007 and 24 November 2008; at Manhattan they were harvested on 28 November 2007 and 23 November 2008. Harvested plot center areas were 1.2 m by 10.7 m and 0.91 m by 10.7 m in 2007 and 2008, respectively. Harvested stover was dried in a forced-air dryer at 65° C for 240 hours. Sub-samples were randomly extracted from the harvested biomass to determine harvest DM and nutrient concentrations.

Dry matter concentrations for grain and stover were calculated on a wet mass basis. Stover yields included all above-ground harvested biomass less grain, and were standardized to dry yields using the calculated stover DM concentration. Grain yields include threshed grain only, and were standardized to dry yield using the DM concentration at the time of threshing. Grain DM concentration was calculated from the threshed grain moisture content (MC) measured with a Dickey-john GAC 2000 grain analysis computer (DICKEY-john Corp., Springfield, IL). Final grain, stover, total biomass, and FC yields were extrapolated from individual plot yields. A detailed analysis of these yields is provided in Chapter 2.

Nitrogen, P and K concentrations of grain and stover were obtained for all crops in both years. Nutrient removal by sweet sorghum stover in 2007 was found by combining the extracted juice and pressed bagasse/leaf nutrient removal values. In 2008, additional whole plant samples of sweet sorghum were harvested, dried, and analyzed for stover nutrient concentrations. Dried stover samples were ground with a Model 4 Thomas-Wiley Laboratory Mill equipped with a 2 mm screen (Thomas Scientific, Swedesboro, NJ). Dry grain samples were initially ground to ≤ 1 mm particle size with a UDY Cyclone Sample Mill (UDY Corporation, Boulder, CO), then processed once more with a high energy ball-mill for complete homogeneity of the sample. Grain and stover were analyzed for total N, P, and K using the sulfuric acid/hydrogen peroxide wet digestion method by the KSU Soil Testing Laboratory (Miller and Miller, 1948; Thomas et al., 1967). Once digested, samples were analyzed simultaneously using a Technicon AAII AutoAnalyzer (SEAL Analytical Inc., Mequon, WI) and a colorimetric Industrial Method 334-74W/B utilizing separate channels to determine N and P concentration levels. Potassium concentrations were analyzed after digestion using Flame Atomic Absorption (KSU Soil Testing Laboratory, 2009). Nutrient removal by harvested components of individual plots was calculated as the product of grain or stover DM yield and nutrient concentration.

Extracted sweet sorghum juice samples from 2007 were analyzed for total N, P and K concentrations. Sub-samples from individual plots were stored at 3° C within 12 hours of extraction. The sub-samples were digested with Potassium Persulfate reagent in an autoclave, then analyzed using a Technicon AAII AutoAnalyzer for P and an Alpkem Rapid Flow Analyzer (Alpkem, Clackamas, OR) for NO_3-N (cadmium reduction method) (KSU Soil Testing Laboratory, 2009). Potassium concentrations were directly found using Inductively Coupled Plasma (ICP) spectrometry (Leman Labs, Hudson, MA). Nutrient removal by extracted juice was calculated as the product of juice mass yield and nutrient concentration. Juice samples were not analyzed in 2008 due to degradation and subsequent loss of sub-samples after harvest

Total biomass nutrient removal amounts for individual plots were calculated from the sum of individual component removal.

Population variance equality of nutrient concentrations within individual harvest components, as well as nutrient removal of these components, was conducted using Hartley's test for homogeneity (Ott, 1988). Significance of main effect differences and their interactions was determined using the PROC GLIMMIX procedure (SAS Institute, 2004) with year or location, and/or variety as fixed effects and replications as random effects. Mean separations were performed for the main effect treatment effects (year or location and/or variety) if the F-tests for treatment effects were significant ($p = 0.05$).

Results

Cumulative in-season (1 April – 31 Oct.) precipitation and GDUs for the two locations in 2007, 2008, and the 30-year normal average are illustrated in Table 3.4 (High Plains Regional Climate Center, 2008). In-season cumulative precipitation was above normal both years at Troy and Manhattan, which normally receive 75.0 and 68.2 cm, respectively. Cumulative in-season GDUs for corn and sorghum were above normal in 2007 at both locations, but below normal in 2008 at each location. At Manhattan, multiple heavy rainfall events caused some flood damage in May and June of both study years.

Grain Nutrient Concentration

Grain nutrient concentration data for 2007 and 2008 were analyzed separately due to unequal population variances of N concentration between the two study years at Troy. Variety was the only significant ($p = 0.05$) main effect observed within individual years (Table 3.5).

Grain P and K concentrations were not different between locations (Table 3.5), even though soil levels of these two nutrients were greater at Troy (Table 3.1). Nitrogen and P concentrations were similar between years, but K content was observed to decrease in 2008 grain crops. Sweet sorghum nutrient concentrations were generally among the highest observed in the study. ‘M81E’ is a long season variety which did not receive sufficient GDUs in either year to complete grain fill, therefore nutrient accumulation was greater than starch accumulation. In 2007, N concentration was greatest for the *bmr* sorghum; however *bmr* and sweet sorghum grain N concentrations were not different in 2008. Rotated corn and CC grain achieved the lowest N concentrations both years; however, N concentration of ‘NK300’ grain was not different than corn 2007. The significantly higher P and K contents of CC grain in 2007, compared with RC, cannot be explained. Phosphorus concentrations of corn and DP FS grain were similar; however they were generally less than those of *bmr* and sweet sorghum. Potassium concentrations in grain were variable among cultivars between years. Dual-purpose FS and *bmr* sorghum grain K concentrations were not different within individual years, but were lower than sweet sorghum. Based upon nutrient concentrations and grain yields (Table 3.6), corn achieved greater DM (starch) accumulation than sorghum, reducing nutrient concentrations overall.

Grain Yield and Nutrient Removal

A significant year x location x variety ($p = 0.05$) interaction was observed for grain yield. Corn produced greater DM yields than sorghum across all site years (Table 3.6). Corn yields ranged from 8.7 to 12 Mg ha^{-1}, with a mean of 10.1 Mg ha^{-1}. Mean CC yields (9.3 Mg ha^{-1}) were less than those produced by RC (11 Mg ha^{-1}) throughout the study, except at Troy in 2008 where yields of the two crops did not differ. Of the sorghum cultivars, DP FS achieved the highest yields (5.3 to 7.6 Mg ha^{-1}), while the *bmr* and sweet sorghum produced the lowest. Field observations identified significant yield losses for *bmr* sorghum due to stalk lodging and grain shattering. Due to its relatively early maturity, bird damage to grain heads of *bmr* sorghum at Troy was observed both years. Soybean DM yields were similar across locations and years, averaging 2851 kg ha^{-1}. See Chapter 2 for full analysis of grain yield.

Grain nutrient removal data for Troy and Manhattan were analyzed separately due to unequal population variance of grain P removal between locations in 2007. A significant year x variety interaction ($p = 0.05$) was observed for K removal at Manhattan; however variety was the only significant main effect for all other nutrient removal amounts at both locations. Nutrient removal was most affected by grain yield variations illustrated in Table 3.6. Nutrient removal was greatest for RC and CC crops at both locations (Table 3.7). Nitrogen removal by CC (110 kg ha^{-1}) at Manhattan was less than RC (88 kg ha^{-1}) due to reduced CC grain yields. Phosphorus removal by corn was observed to be higher at Troy (37 kg ha^{-1}) than Manhattan (26 kg ha^{-1}) due to greater soil P levels at the Troy location. Sorghum P removal did not seem to be significantly impacted by soil P differences between locations. Nutrient removal among DP FS cultivars was not different; however they were generally greater than *bmr* or sweet sorghum due to increased yields. The year x variety interaction observed for K at Manhattan is a result of higher K concentrations in 2007 compared with 2008; and grain yield variations between years at that location.

Stover Nutrient Concentration

Stover nutrient concentrations in 2007 and 2008 were analyzed separately due to unequal population variances found in N concentration between years at Manhattan, and P concentration between years at Troy. A significant location x variety interaction ($p = 0.05$) was observed for all nutrient concentrations each individual year, except K in 2007 which had no interaction, only a significant variety main effect. Stover concentration data for 2007 is reported in Table 3.8, and for 2008 in Table 3.9. Nitrogen and P concentrations were generally higher at Troy, while K concentrations were similar between locations. In 2007, nutrient concentrations of perennial grasses were equal to, or greater than, those of annual crops at both locations, but were significantly reduced in 2008.

Establishment year Miscanthus had the greatest stover N concentration of all crops. Switchgrass and big bluestem also had high N concentrations in 2007 compared with 2008; however 2007 levels at Troy were higher than Manhattan due to the application of N fertilizer at Troy during the establishment year. In 2008, N concentrations of perennial grass cultivars across locations were not different (3912 – 4441 ppm); and were similar to corn at Troy, and corn, ‘NK300’, PS, and sweet sorghum at Manhattan. In 2007, N concentrations of corn and sorghum ranged from 4448 to 7162 ppm across locations. Differences in annual N concentrations between locations were dependent upon individual cultivars. In 2008, sorghum and corn N levels ranged from 4610 to 6878 ppm across locations. At Troy in 2008, corn N concentrations were less than sorghum; however at Manhattan, corn and sorghum N concentrations were similar both years.

Phosphorus concentrations varied considerably by cultivar and location. Phosphorus concentrations in annual crops were higher at Troy due to higher soil P levels compared with Manhattan (Table 3.1). Application of P fertilizer before the 2008 growing season at Manhattan did not increase P concentrations within the plant stover. Corn and sorghum P concentrations in 2007 ranged from 1075 – 1692 ppm at Troy, and 576 - 1249 at Manhattan. In 2008, annual crop P concentrations ranged from 1142 – 2315 ppm at Troy, and 650 – 1184 ppm at Manhattan. Brown mid-rib sorghum had the highest P concentration (1249 ppm) of annual crops at Manhattan in 2007. Sweet sorghum was generally found to have P concentrations equal to, or less than other sorghum and corn cultivars, except at Troy in 2007 where sweet sorghum P concentrations were among the highest of all crops. Perennial grasses did not follow the same location difference trend as annual crops. Phosphorus concentrations of perennial grass stover at Troy were generally equal to, or less than, those at Manhattan. The exception to this pattern was big bluestem in 2008, which had higher P concentrations at Troy. In 2008, Miscanthus P concentrations were of the lowest observed in the study (387 ppm), not differing between locations.

Annual crop stover K concentrations varied among cultivars, but did not differ greatly between locations. Average perennial grass K concentrations were greater in 2007 (11 719 ppm) than in 2008 at Troy (6930 ppm) and Manhattan (3757 ppm). In 2008, K concentrations of big bluestem were higher at Troy than Manhattan; however Miscanthus and switchgrass K levels were not different between locations. 'DKS59-09' DP FS had the highest K concentrations of all crops in both years. Potassium concentrations of annual crops in 2007 were lowest for corn and sweet sorghum. A similar trend was found at Manhattan in 2008; however K concentration of corn was not different than PS or *bmr* sorghum, but less than the DP FS cultivars.

Stover Yield and Nutrient Removal

Stover yield data presented in this discussion were analyzed separately between locations to coincide with stover nutrient removal data analysis. A significant year x variety interaction ($p = 0.05$) was observed for stover yield data at individual locations; the same interaction observed in Chapter 2 when stover yield data from all four site years were analyzed together. The greatest stover yields were produced by sweet sorghum in 2008 at Troy (32.4 Mg ha^{-1}) and Manhattan (29.8 Mg ha^{-1}), reported in Tables 3.10 and 3.1l, respectively. At Troy, severe root lodging (>95%) was observed for some sweet sorghum plots in 2007 and all plots in 2008 at Troy causing harvest difficulty, but yields were not noticeably impacted. Stover DM yields of *bmr* sorghum were likely reduced by severe stalk lodging (>95%) which was observed for all *bmr* sorghum plots throughout the study as grain fill progressed. Stover yields of PS and sweet sorghum were not different in 2007; however Manhattan PS sorghum yields in 2008 were less than PS sorghum yields in 2007, and sweet sorghum both years. At both locations in 2007, establishment year perennial WS grass yields were generally less than annual crop yields, ranging from 2.7 to 3.8 Mg ha^{-1} at Manhattan and 4.0 to 5.1 Mg ha^{-1} at Troy. Stover yields of perennial grasses increased significantly in 2008 due to improved stand establishment. A full analysis of stover yield, harvest moisture, and harvest height data is provided in Chapter 2.

Stover nutrient removal at Troy and Manhattan was analyzed separately due to unequal population variances of P removal between locations in 2007. A significant year x variety interaction ($p = 0.05$) was observed for individual nutrient removal at each location (Tables 3.10 and 3.11). Overall, nutrient removal was observed to be higher at Troy than Manhattan, due to higher soil nutrient levels at Troy. Annual crop stover nutrient removal levels varied between cultivars; and was significantly influenced by stover yield and nutrient concentration of the respective cultivar. Perennial grass nutrient removal was similar between cultivars or years, even though stover yields were greater in 2008 at both locations. Average removal by perennial grass cultivars across years at Troy were 44 kg N ha^{-1} , 7 kg P ha^{-1}, and 67 kg K ha^{-1}; compared with 31 kg N ha^{-1}, 5 kg P ha^{-1}, and 33 kg K ha^{-1} at Manhattan. Nutrient removal by PS and sweet sorghum were among the greatest found in the study due to their high stover yields. Mean removal by these two crops across years was 167 kg N ha^{-1}, 40 kg P ha^{-1}, and 355 kg K ha^{-1} at Troy; and 132 kg N ha^{-1}, 21 kg P ha^{-1}, and 311 kg K ha^{-1} at Manhattan. Rotated and CC removal levels did not differ at individual locations; however they were generally less than sorghum.

Nutrient removal by DP FS and *bmr* cultivars was greater than corn, but generally less than PS or sweet sorghum.

Sweet Sorghum Juice Yield, Nutrient Concentration, and Nutrient Removal

Sweet sorghum juice was analyzed in 2007 only, due to degradation and subsequent loss of extracted juice samples in 2008. A significant location x variety interaction ($p = 0.05$) was observed for P and K concentrations, as well as P removal. There was no difference between locations for juice yield, N concentration, and N and K nutrient removal (Table 3.12). Root lodging (>95%) of replication four at Troy negatively impacted juice yields of that plot, however differences in nutrient concentrations were not observed. Nitrogen concentration and total removal by sweet sorghum juice was minimal. Phosphorus concentration and total removal was greater at Troy (142 ppm and 5 kg P ha^{-1}, respectively) than at Manhattan (40 ppm and 1.2 kg P ha^{-1}, respectively). Potassium accumulation in sweet sorghum juice was the greatest of all nutrients. At Troy, K concentration was greater than at Manhattan (1825 vs. 1447 ppm). Higher P and K soil levels at Troy likely allowed for greater accumulation of these nutrients in the sweet sorghum juice compared with Manhattan.

Total Biomass Yield and Nutrient Removal

Total biomass yield data presented in this discussion were analyzed separately between locations to coincide with total biomass nutrient removal data analysis (Tables 3.13 and 3.14). A significant year x variety interaction ($p = 0.05$) was observed for yield data at individual locations; the same interaction observed in Chapter 2 when total biomass yield data from all four site years were analyzed together. Total biomass yields of annual crops were greater than perennial grasses at both locations. Perennial grass yields improved significantly in 2008. The highest total biomass yields were produced by sweet sorghum both years in Troy (31 Mg ha^{-1}), and Manhattan in 2008 (32 Mg ha^{-1}). At Troy, PS sorghum yields across years were not different than RC or 'NK300' DP FS in 2007. Average corn and DP FS yields were similar across years at individual locations; averaging 19.9 Mg ha^{-1} at Troy and 19.5 Mg ha^{-1} at Manhattan. A complete discussion of yield results is provided in Chapter 2.

Total biomass nutrient removal at Troy and Manhattan was analyzed separately due to unequal population variance of P removal between locations in 2007. A significant year x variety interaction ($p = 0.05$) was observed for all nutrients at Troy and Manhattan. Variation in nutrient removal between years, at each location, was most dependent upon yield variation (Tables 3.13 and 3.14). Annual crop nutrient removal was greater than those of perennial grasses. Nutrient removal varied among annual cultivars; however removal by perennial grasses was generally not different at individual locations between years. Perennial grass biomass was harvested as stover only, therefore stover and total biomass nutrient data are not different.

Nutrient removal at Troy is reported in Table 3.13. Total biomass N removal was greatest for sweet sorghum across years, and RC, CC and 'NK300" DP FS in 2007, averaging 193 kg N ha^{-1}. Rotated corn N removal was less in 2008 than 2007 (150 vs. 205 kg N ha^{-1}) due to reduced total biomass yield. Brown mid-rib sorghum N removal in 2008 (127 kg N ha^{-1}) was greater than 2007 (90 kg N ha^{-1}) due to increased yield in 2008. Phosphorus removal was greatest for sweet sorghum, RC and CC in 2008, along with RC and 'DKS59-09' in 2007, averaging 49 kg P ha^{-1}. Photoperiod sensitive sorghum in 2007 had the greatest K removal (411 kg K ha^{-1}) of all crops across years. In 2008, PS sorghum K removal was not different than sweet sorghum and DP FS cultivars across years, averaging 323 kg K ha^{-1}. Corn removed less K than sorghum, with average removal of 173 kg K ha^{-1}.

Nutrient removal at Manhattan is illustrated in Table 3.14. Similar to Troy, N removal was greatest for sweet sorghum and RC (177 kg N ha^{-1}) across years. ‘DKS59-09’ N removal was greater in 2008 than 2007 (176 vs. 136 kg N ha^{-1}) due to a significant stover yield increase in 2008. In 2008, *bmr* sorghum N removal was less than 2007 (95 vs. 130 kg ha^{-1}), even though total biomass yields were not different; opposite of trends observed at Troy. Corn P removal (34 kg ha^{-1}) was greater than sorghum (24 kg ha^{-1}), except ‘DKS59-09’ in 2008 which was not different than either corn rotation. Phosphorus removal was similar between sorghum cultivars across years, ranging from 21 to 33 kg ha^{-1}. Mean K removal (315 kg ha $^{-1}$) was greatest for sweet and PS sorghum across years, as well as ‘DKS59-09’ in 2008. Corn K removal (153 kg ha^{-1}), was less that sorghum; however was not different between rotations.

Discussion

Yields varied not only between annual and perennial crops, but among annual cultivars as well. Individual annual cultivar yields were similar across years and locations due to similar soil characteristics and above normal precipitation amounts. Below normal cumulative in-season GDUs in 2008 did not generally affect crop yields; however may be responsible for the reduced vegetative DM yield of PS and grain yield of ‘NK300’ sorghum compared with 2007 yields. Perennial grass yields were similar across locations; increasing significantly from the 2007 establishment year to 2008. As perennial grasses become established over a two to six year period, depending upon species and environment, yields will likely increase and be sustainable for multiple years with proper management (Christian et al., 2008; Sanderson, 2004). The yield potential of Miscanthus is greater than that of switchgrass or big bluestem, thus may take longer to achieve full production establishment. Grain nutrient concentration was influenced mainly by cultivar, not location. Nutrient concentrations of stover varied due to cultivar and/or location, depending upon the individual nutrient and year. Grain, stover, and total biomass nutrient removal was significantly influenced by yield differences between annual and perennial crops, as well as between annual cultivars. Overall, higher yielding crops removed higher amounts of individual nutrients.

Cultivar selection accounted for most variability in grain yield and nutrient accumulation. Corn achieved the highest grain yields and nutrient removal amounts at both locations, even though grain nutrient concentrations were generally lower for corn than the sorghum cultivars. Rotation effects were generally not observed for corn grain nutrient removal. Sweet sorghum accumulated the highest grain nutrient concentrations of all annual crops; likely due to lack of physiological maturity and subsequent reduced grain fill both years. The reduced N concentrations of corn may implicate lower protein levels and higher starch concentrations; thus higher ethanol yields of corn compared with sorghum grain. Brown mid-rib and sweet sorghum had the lowest grain nutrient removal across locations, explained by their low overall grain production. Based upon N concentrations, high protein accumulation and low grain yields of sweet and *bmr* sorghum, their potential utilization for grain ethanol production may be minimal. Overall nutrient removal and replacement requirements for harvested grain are similar to those reported by Hossain (2006) and Leikam et al. (2003).

Most annual crop stover N and K concentration variability was accounted for by cultivar selection. In addition, P concentrations were influenced by soil nutrient level differences between locations. Sweet and PS sorghum cultivars had the greatest overall stover nutrient removal due to their high stover yields, compared with all other crops. At Troy, stover nutrient concentrations and removal were generally lower for corn due to stover accumulation being less than sorghum. At Manhattan, corn and sorghum stover yields were similar; therefore N and P removal were generally not different. Potassium removal by sorghum stover was greater than corn at both locations.

Stover nutrient removal by perennial crops was much less than annual crops throughout the study as a result of lower stover yields. Perennial grass stover nutrient concentrations were most influenced by year and cultivar, except N concentrations in 2007 which were greater at Troy due to N fertilizer application. Although perennial grass yields increased in 2008, nutrient removal did not change due to fluctuations in nutrient concentrations. Higher P concentrations were found at Troy, which had much higher soil P levels. Stover nutrient concentrations, especially N and K, were greatest in the 2007 establishment year. High N concentrations of establishment year grass biomass is explained by Cosentino et al. (2007), which reported that leaf DM of Miscanthus, in the establishment year, makes up 60% of the stover biomass; and contains a much higher N concentration than the stem components. In following years, the ratio of leaf DM to stem DM is reduced, especially if harvest is delayed until after dormancy, therefore N concentrations decrease. Sander (2007) reported that K concentrations can vary between years due to precipitation leaching K from plant tissue, which was likely a factor in 2008.

Extracted sweet sorghum juice yields and N accumulation did not differ between locations in 2007. Soil P and K level differences between locations did influence the P and K concentrations and total removal by extracted juice. Concentrations of P and K are similar to those reported by Fenzhou (1989). Phosphorus removal by juice at Troy and Manhattan made up 10% and 6%, respectively, of the sweet sorghum total biomass P removal. Potassium removal by extracted juices represented 19% and 15% of the total biomass K removal.

Overall, total biomass nutrient removal was influenced most by yield differences between annual and perennial crops; however removal trends were generally higher at Troy than Manhattan. Total biomass yields, and subsequent nutrient removals, were greater for corn and sorghum than perennial grasses. Nutrient removal among annuals varied by cultivar; however the greatest total biomass yields did not necessarily reflect the greatest removal amounts for all nutrients. Rotation did not impact total nutrient removal by corn. Sweet and PS sorghum cultivars were found to produce 25% - 50% higher total biomass yields than corn with equal, or reduced, N and P removal. These findings coincide with data reported by Anderson et al. (1995) and Bean et al. (2008), who reported similar findings. Potassium removal by sorghum was significantly higher than corn. At low soil P levels (Manhattan), P removal by corn was greater than sorghum; however this trend was not as apparent under higher soil P growing conditions at Troy. Fertilizer P and K applied before the 2008 growing season did not clearly impact yield or nutrient removal within the same year. Phosphorus and K removal by corn total biomass was similar to corn silage DM removal rates (2.0 kg P Mg^{-1} and 10.3 kg K Mg^{-1}) reported by Leikam et al. (2003). Sorghum silage DM K rates were reported to be the same as corn by Leikam et al. (2003); however sorghum K removal at both locations in this study was found to be significantly higher than corn.

Results of the study suggest that corn will remain the best crop selection for grain based ethanol production in areas where its yield potential is equal to, or higher than, that of grain sorghum. As cellulosic ethanol processes develop, and producers harvest higher percentages of stover DM, nutrient removal must be replenished at rates similar to those used for corn or sorghum silage. Fertilizer inputs to replace nutrients removed by the total biomass of corn or sorghum will significantly impact the economics of LC biomass energy conversion processes.

High concentrations of K within sorghum stover may lead to utilization problems if alternately used in direct combustions processes to generate heat. Photoperiod and sweet sorghum were found to produce greater total biomass yields than corn or other sorghum cultivars with similar, or reduced, N and P removal rates; thus increasing their energy production efficiency. The use of perennial grass crops to supply LC biomass is promising from an energy input and nutrient removal perspective. Once established these crops are able to produce LC biomass containing minimal nutrient concentrations and will require relatively low fertilizer inputs due to their ability to translocate and store nutrients between growing seasons; however harvest timing and management is critical. The results of this study provide data for N, P, and K removal estimation, based upon biomass yield and nutrient concentrations, of annual and perennial biofuel crops which can be utilized by agricultural and energy producers for nutrient management and economic evaluation of biofuel cropping systems.

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Chapter 3 – Tables

Table 3.1. Pre-plant soil test results in 2007 at Troy and Manhattan.

Location	Depth	pH	P	K	NH_4-N	NO_3-N	OM
	cm		ppm	ppm	ppm	ppm	%
Troy†	0-15	6.9	83	331	54	40	3.2
	15-30	6.3	47	173	12	22	2.7
Manhattan	0-15	6.6	15	195	6.8	57	2.5
	15-30	6.7	6	121	2.7	8	2.3

† Anhydrous ammonia (82-0-0) applied in fall prior to soil sampling.

Table 3.2. Planting, nitrogen fertilization, and harvest dates and seeding and fertilizer rates of annual crops in 2007 at Troy and Manhattan.

Location	Cultivar	Planting Date	Target Seeding Rate	Nitrogen Rate†	Nitrogen Application Date	Harvest Date
Troy			seeds ha^{-1}	kg N ha^{-1}		
	PS 1990CA	16 May	143 000	180	Nov. 2006	27 Oct.
	Sweet M81E	16 May	143 000	180	Nov. 2006	27 Oct.
	DP FS NK300	16 May	143 000	180	Nov. 2006	12 Oct.
	DP FS DKS59-09	16 May	143 000	180	Nov. 2006	12 Oct.
	BMR GW8528	16 May	143 000	180	Nov. 2006	27 Oct.
	Rotated Corn 33K40	19 Apr.	68 000	180	Nov. 2006	12 Oct.
	Continuous Corn 33K40	19 Apr.	68 000	180	Nov. 2006	12 Oct.
	Soybean 3824RR	16 May	250 000	180	Nov. 2006	2 Oct.
Manhattan						
	PS 1990CA	21 May	143 000	168	22 May	23 Oct.
	Sweet M81E	21 May	143 000	168	22 May	25 Oct.
	DP FS NK300	21 May	143 000	168	22 May	23 Oct.
	DP FS DKS59-09	21 May	143 000	168	22 May	11 Oct.
	BMR GW8528	21 May	143 000	168	22 May	23 Oct.
	Rotated Corn 33K40	14 May	68 000	168	22 May	29 Sept.
	Continuous Corn 33K40	14 May	68 000	168	22 May	29 Sept.
	Soybeans KSU3406RR	14 May	250 000	-	-	2 Nov.

†Nitrogen fertilizer applied pre-plant as 82-0-0 at Troy and side-dress as 46-0-0 at Manhattan.

Table 3.3. Planting, nitrogen fertilization, and harvest dates and seeding and fertilizer rates of annual crops in 2008 at Troy and Manhattan.

Location	Cultivar	Planting Date	Target Seeding Rate	Nitrogen Rate†	Nitrogen Application Date	Harvest Date
Troy			seeds ha^{-1}	kg N ha^{-1}		
	PS 1990CA	30 May	191 000	180	4 June	27 Oct.
	Sweet M81E	30 May	191 000	180	4 June	10 Oct.
	DP FS NK300	30 May	191 000	180	4 June	27 Oct.
	DP FS DKS59-09	30 May	191 000	180	4 June	27 Oct.
	BMR GW8528	30 May	191 000	180	4 June	26 Sept.
	Rotated Corn 33K44	23 Apr.	68 000	180	4 June	26 Sept.
	Continuous Corn 33K44	23 Apr.	68 000	180	4 June	26 Sept.
	Soybeans KSU3406RR	30 May	296 000	-	-	12 Oct.
Manhattan						
	PS 1990CA	21 May	191 000	180	17 June	20 Oct.
	Sweet M81E	21 May	191 000	180	17 June	3 Oct.
	DP FS NK300	21 May	191 000	180	17 June	20 Oct.
	DP FS DKS59-09	21 May	191 000	180	17 June	20 Oct.
	BMR GW8528	21 May	191 000	180	17 June	17 Sept.
	Rotated Corn 33K44	22 Apr.	68 000	180	17 June	17 Sept.
	Continuous Corn 33K44	22 Apr.	68 000	180	17 June	17 Sept.
	Soybeans KSU3406RR	21 May	296 000	-	-	18 Nov.

†Nitrogen fertilizer applied side-dress as 46-0-0 at both locations

Table 3.4. In-season cumulative growing degree units and precipitation.

Location/ Crop	Growing Degree Units†‡			Precipitation†		
	2007	2008	Normal	2007	2008	Normal
		GDUs			cm	
Troy				80.2	86.8	75.0
Corn	3950	3498	3648			
Sorghum	4127	3563	3724			
Manhattan				88.3	93.6	68.2
Corn	4240	3601	3866			
Sorghum	4619	3806	4028			

† Growing season considered 1 April - 31 October of each year. GDUs and precipitation data from High Plains Regional Climate Center (2008).

‡ Base temperature of 10º C used for GDU calculation.

Table 3.5. Nutrient (N, P, K) concentration in grain of annual crops in 2007 and 2008.

	2007						2008					
Cultivar	N		P		K		N		P		K	
	ppm											
Rotated corn	12 076	c†	2 889	c	3 939	d	10 783	c	3 198	c	3 779	b
Continuous corn	11 679	c	3 474	ab	5 036	a	10 786	c	3 005	c	3 699	b
DP FS DKS59-09	14 109	b	3 133	bc	4 752	abc	13 019	b	3 235	c	3 164	c
DP FS NK300	12 039	c	2 749	c	4 312	bcd	14 020	b	3 159	c	3 151	c
BMR GW8528	15 870	a	3 203	abc	4 227	cd	15 852	a	3 725	b	3 356	c
Sweet Sorg. M81E	13 658	b	3 601	a	4 896	ab	17 008	a	4 066	a	4 556	a

† Mean nutrient concentrations followed by the same letter, within the same column, are not different, $p = 0.05$.

Table 3.6. Grain dry matter yields of annual crops at Troy and Manhattan in 2007 and 2008.

Cultivar	Grain Yield							
	Troy				Manhattan			
	2007		2008		2007		2008	
	Mg ha^{-1}							
Rotated Corn	12.0	a†	10.0	bc	10.0	bc	11.0	ab
Continuous Corn	10.2	bc	10.0	bc	8.7	de	9.1	cd
DP FS NK300	7.5	f	5.9	gh	7.6	ef	5.0	hi
DP FS DKS59-09	6.3	g	6.2	g	5.6	gh	5.3	hij
BMR GW8528	2.5	jk	1.5	jkl	4.4	i	2.7	j
Sweet Sorg. M81E	2.1	jk	0.7	l	1.5	kl	2.1	jk

† Mean yields across locations and years with the same letter are not different, *p* = 0.05.

Table 3.7. Nutrient (N, P, K) removal by grain of annual crops at Troy and Manhattan.

Cultivar	Troy						Manhattan							
	N		P		K		N		P		K			
											2007		2008	
	kg ha^{-1}													
Rotated corn	132	a†	37	a	43	a	110	a	27	a	39	ab‡	36	abc
Continuous corn	122	a	37	a	46	a	88	b	24	a	41	a	30	cd
DP FS DKS59-09	85	b	21	b	25	b	74	b	16	b	27	d	16	ef
DP FS NK300	90	b	21	b	26	b	78	b	17	b	34	bcd	15	efg
BMR GW8528	33	c	8	c	9	c	56	c	11	c	19	e	9	fgh
Sweet Sorg. M81E	20	c	5	c	7	c	28	d	7	d	7	h	8	gh

† Mean nutrient removal followed by the same letter, within the same column, are not different, *p* = 0.05.

‡ Mean K removal followed by the same letter, across 2007 and 2008, are not different, *p* = 0.05.

Table 3.8. Stover nutrient (N, P, K) concentration of annual and perennial crops in 2007 at Troy and Manhattan.

	N		P		K
	Troy	Manhattan	Troy	Manhattan	
			ppm		
Rotated corn	4797 ijkl[†]	4667 jkl	1238 def[¶]	621 j	10158 e[‡]
Continuous corn	5333 hijkl	4467 kl	1075 fgh	702 ij	10877 de
DP FS DKS59-09	7113 cdef	7162 cde	1341 cde	958 gh	21984 a
DP FS NK300	6473 efgh	4485 kl	1482 bcd[¶]	685 ij	17656 b
BMR GW8528	5824 ghij	5770 ghij	1692 a	1249 def[§]	15206 bc
PS 1990CA	6265 efgh	4448 l	1561 ab	846 hi	13397 cd
Sweet Sorg. M81E	6483 efgh	6675 defg	1511 abc	576 j	11723 de
Miscanthus	11176 a	9581 b	896 hi	837 hi	10954 de
Big bluestem	8101 c	5641 ghijk	1227 ef	1309 cdef	11678 de
Switchgrass	7920 cd	5890 fghi	1199 efg	1483 abcd[§]	12526 cde

[†] Means for individual nutrient x locations followed by the same letter are not different, *p* = 0.05.
[‡] Mean K concentrations followed by the same letter are not different, *p* = 0.05.
[§] Mean P concentrations are different, *p* = 0.05, despite having common letters.
[¶] Mean P concentrations are different, *p* = 0.05, despite having common letters.

Table 3.9. Stover nutrient (N, P, K) concentration of annual and perennial crops in 2008 at Troy and Manhattan.

Cultivar	N		P		K	
	Troy	Manhattan	Troy	Manhattan	Troy	Manhattan
	ppm					
Rotated corn	4255 ef[†]	4395 ef	1453 cd	833 gh	15437 ef	12891 fg
Continuous corn	4628 def	4205 ef	1242 de	687 hi	14466 ef	11205 gh
DP FS DKS59-09	6566 a	5890 abcd[‡]	1766 bc	918 efgh	22491 a	19708 abc
DP FS NK300	6655 a	4610 ef	1812 b	825 gh	21037 ab	16027 de
BMR GW8528	6878 a	5195 bcde	2315 a	1099 defg	17235 cde	18759 bcd
PS 1990CA	6270 ab	4739 cdef[‡]	1703 bc	1184 def	14708 ef	15213 ef
Sweet M81E	5937 abc	4537 ef	1142 defg	650 hi	11008 gh	10809 gh
Miscanthus	4441 ef	3981 f	381 i	392 i	6114 ij	3799 jk
Big bluestem	4436 ef	3912 f	1150 defg	682 hi	8342 hi	3030 k
Switchgrass	4376 ef	4924 cdef	853 fgh	916 efgh	6333 ij	4442 jk

[†] Means for individual nutrient x locations followed by the same letter are not different, $p = 0.05$.
[‡] Mean N concentrations are different, $p = 0.05$, despite having common letters.

Table 3.10. Stover yields and nutrient (N, P, K) removal by annual and perennial crops at Troy in 2007 and 2008.

	Stover Yield				N				P				K			
	2007		2008		2007		2008		2007		2008		2007		2008	
	Mg ha^{-1}				kg ha^{-1}											
Rotated corn	10.8	cdef	9.0	efg‡	52	ef†	38	ef	13	def	13	def	135	fg	138	fg
Continuous corn	9.8	def	8.6	fgh	52	ef	40	ef	11	defg	11	defg	119	fgh	124	fgh
DP FS DKS59-09	11.5	cdef	14.1	c	81	cd	93	c	15	d	25	c	258	de	316	bcd
DP FS NK300	14.9	c	12.8	cde	95	c	85	c	22	c	23	c	294	bcde	269	cde
BMR GW8528	9.0	efg	14.5	c	51	ef	100	c	15	de	33	b	152	f	248	e
PS 1990CA	26.8	b	22.7	b	169	a	142	b	42	a	39	ab	411	a	333	b
Sweet M81E	26.7	b	32.4	a	174	a	182	a	41	a	36	ab	330	bc	344	b
Miscanthus	4.0	i	13.7	cd	44	ef	60	de	4	h	5	gh	45	i	83	ghi
Big bluestem	5.1	ghi	7.8	fghi	41	ef	35	f	6	gh	9	fgh	71	hi	65	hi
Switchgrass	4.7	hi	11.2	cdef	37	ef	47	ef	6	gh	9	efgh	69	hi	67	hi

† Means of individual nutrient removal x years followed by the same letter are not different, *p* = 0.05.

‡ Mean yields followed by the same letter across years are not different, *p* = 0.05.

Table 3.11. Stover yields and nutrient (N, P, K) removal by annual and perennial crops at Manhattan in 2007 and 2008.

	Stover Yield		N		P		K	
	2007	2008	2007	2008	2007	2008	2007	2008
	Mg ha^{-1}		kg ha^{-1}					
Rotated corn	11.3 ef‡	11.3 ef	53 fg†	47 ghi	7 def	8 de	92 hi	134 fgh
Continuous corn	11.8 ef	10.3 fgh	52 fgh	39 ghij	8 d	7 def	115 h	102 h
DP FS DKS59-09	8.2 ghi	13.7 de	58 fg	84 ed	8 de	13 c	179 ef	270 bc
DP FS NK300	11.4 ef	15.5 d	51 fgh	71 ef	8 de	13 c	175 efg	246 cd
BMR GW8528	9.8 fghi	11.0 efg	57 fg	57 fg	12 c	12 c	126 gh	206 de
PS 1990CA	26.8 b	22.2 c	119 bc	103 cd	23 ab	25 a	303 ab	327 a
Sweet M81E	26.1 b	29.8 a	170 a	137 b	15 c	19 b	293 abc	321 a
Miscanthus	2.7 j	11.8 ef	26 ij	48 fghi	2 g	4 fg	27 j	43 ij
Big bluestem	3.8 j	7.7 hi	22 j	30 hij	5 efg	5 defg	37 j	23 j
Switchgrass	3.6 j	7.2 i	21 j	36 ghij	5 defg	6 def	37 j	32 j

† Means of individual nutrient removal x years followed by the same letter are not different, *p* = 0.05.
‡ Mean yields followed by the same letter across years are not different, *p* = 0.05.

Table 3.12. Nutrient (N, P, K) concentration and total removal of extracted sweet sorghum juice in 2007 at Troy and Manhattan.

	Troy		Manhattan	
Juice Yield (Mg ha^{-1})	34.8	a†	30.8	a
Concentration (ppm)				
N	250	a	240	a
P	142	a	40	b
K	1825	a	1447	b
Removal (kg ha^{-1})				
N	8.3	a	7.4	a
P	5.0	a	1.2	b
K	63.7	a	44.7	a

† Mean values in the same row followed by the same letter are not different, p = 0.05.

Table 3.13. Total biomass yields and nutrient (N, P, K) removal by annual and perennial crops at Troy in 2007 and 2008.

	Total Biomass Yield		N		P		K	
	2007	2008	2007	2008	2007	2008	2007	2008
	Mg ha^{-1}		kg ha^{-1}					
Rotated corn	22.8 cd[‡]	18.9 def	205 a[†]	150 efg	54 a	47 abcd	182 d	176 d
Continuous corn	20.0 def	18.6 def	177 abcde	159 def	51 ab	43 bcde	173 d	162 d
DP FS DKS59-09	17.8 efg	20.3 def	169 cdef	174 bcde	37 e	46 abcd	287 cb	337 b
DP FS NK300	22.4 cde	18.7 def	187 abcd	173 bcde	45 bcde	43 bcde	325 b	289 cb
BMR GW8528	11.6 hij	16.0 fgh	90 h	127 g	24 f	40 cde	163 d	254 c
PS 1990CA	26.8 bc	22.7 cd	169 cdef	142 fg	42 cde	39 de	411 a	333 b
Sweet Sorg. M81E	28.8 ab	33.1 a	202 ab	194 abc	49 abc	39 de	341 b	347 b
Miscanthus	4.0 k	13.7 ghi	44 i	60 hi	4 g	5 g	45 e	83 e
Big bluestem	5.1 k	7.8 jk	41 i	35 i	6 g	9 g	71 e	65 e
Switchgrass	4.7 k	11.2 ij	37 i	47 i	6 g	9 g	69 e	67 e

[†] Means of individual nutrient removal x years followed by the same letter are not different, $p = 0.05$.
[‡] Mean yields followed by the same letter across years are not different, $p = 0.05$.

Table 3.14. Total biomass yields and nutrient (N, P, K) removal by annual and perennial crops at Manhattan in 2007 and 2008.

	Total Biomass Yield		N		P		K	
	2007	2008	2007	2008	2007	2008	2007	2008
	Mg ha^{-1}		kg ha^{-1}					
Rotated corn	21.3 c‡	22.2 c	167 ab†	176 a	32 bc	39 a	131 e†	179 de
Continuous corn	20.6 c	19.4 c	148 bcd	137 de	34 ab	32 bc§	156 e	145 e
DP FS DKS59-09	13.7 d	19.0 c	136 de	176 a	24 de	33 b	206 d	314 a
DP FS NK300	19.0 c	20.5 c	141 cde	136 de	27 cd	27 cd	209 d	262 bc
BMR GW8528	14.2 d	13.7 d	130 def	95 g	25 de	21 e	145 e	214 cd
PS 1990CA	26.8 b	22.2 c	119 efg	103 fg	23 de	25 de	303 ab	327 a
Sweet Sorg. M81E	27.6 b	32.0 a	192 a	171 ab	20 e	27 cd§	300 ab	330 a
Miscanthus	2.7 f	11.8 d	26 hi	48 h	2 f	4 f	27 f	43 f
Big bluestem	3.8 f	7.7 e	22 hi	30 hi	5 f	5 f	37 f	23 f
Switchgrass	3.6 f	7.2 e	21 i	36 hi	5 f	6 f	37 f	32 f

† Means of individual nutrient removal x years followed by the same letter are not different, $p = 0.05$.
‡ Mean yields followed by the same letter across years are not different, $p = 0.05$.
§ Mean nutrient removal amounts are different, $p = 0.05$, despite having common letters.