Corn and forage sorghum yield and water use in Western Kansas

by

Jason Waite

B.S., Kansas State University, 2008
M.S., Kansas State University, 2010

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2016

Abstract

The Ogallala Aquifer is a large underground water source located under the High Plains and is used as the primary irrigation source for producers in the region. Hyper-extraction of the Ogallala is causing a reduction in irrigation capacity for a large part of the region. Confined animal feeding operations in western Kansas rely upon irrigated crops, mainly corn [*Zea mays* (L.)] as a source of feed. Research has shown that forage sorghum [*Sorghum bicolor* (L.) Monech] could meet the demands of the confined animal feeding operations while using less water than corn. An experiment was designed to evaluate corn and forage sorghum in Western Kansas. The objective of this research was to evaluate the water use and growth characteristics of irrigated and dryland corn and forage sorghum. Field experiments were conducted at two locations (Tribune Experiment Station, Tribune and a cooperator's field near Hoxie, Sheridan County Kansas) in 2011-2013. The experimental design at Tribune was a randomized complete block with four replications. A traditional replicated design was not possible at Hoxie. Multiple subsamples per plot were obtained and data are reported as means with standard errors. Corn and forage sorghum were grown under both dryland and fully irrigated conditions at both locations. Neutron access tubes were installed to monitor soil water. Aboveground biomass, intercepted solar radiation and volumetric soil water content were recorded at 5 sampling dates each growing season. Water use was similar between irrigated corn and forage sorghum. There were differences in biomass from year to year between the irrigated crops. Dryland water use was similar between the two crops and also had differences in biomass from year to year. Yields were significantly lower than average for all crops in 2012 due to drought conditions. Solar radiation interception correlated with aboveground biomass measurements. Aboveground biomass from the forage sorghum and corn was ensiled both years and analyzed for nutrient composition. This research suggests that forage sorghum silage may be an acceptable replacement for corn silage in areas with reduced irrigation capacities.

Corn and forage sorghum yield and water use in Western Kansas

by

Jason Waite

B.S., Kanas State University, 2008
M.S., Kansas State University, 2010

A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2016

Approved by:

Major Professor
P.V. Vara Prasad

Copyright

Abstract

The Ogallala Aquifer is a large underground water source located under the High Plains and is used as the primary irrigation source for producers in the region. Hyper-extraction of the Ogallala is causing a reduction in irrigation capacity for a large part of the region. Confined animal feeding operations in western Kansas rely upon irrigated crops, mainly corn [*Zea mays* (L.)] as a source of feed. Research has shown that forage sorghum [*Sorghum bicolor* (L.) Monech] could meet the demands of the confined animal feeding operations while using less water than corn. An experiment was designed to evaluate corn and forage sorghum in Western Kansas. The objective of this research was to evaluate the water use and growth characteristics of irrigated and dryland corn and forage sorghum. Field experiments were conducted at two locations (Tribune Experiment Station, Tribune and a cooperator's field near Hoxie, Sheridan County Kansas) in 2011-2013. The experimental design at Tribune was a randomized complete block with four replications. A traditional replicated design was not possible at Hoxie. Multiple subsamples per plot were obtained and data are reported as means with standard errors. Corn and forage sorghum were grown under both dryland and fully irrigated conditions at both locations. Neutron access tubes were installed to monitor soil water. Aboveground biomass, intercepted solar radiation and volumetric soil water content were recorded at 5 sampling dates each growing season. Water use was similar between irrigated corn and forage sorghum. There were differences in biomass from year to year between the irrigated crops. Dryland water use was similar between the two crops and also had differences in biomass from year to year. Yields were significantly lower than average for all crops in 2012 due to drought conditions. Solar radiation interception correlated with aboveground biomass measurements. Aboveground biomass from the forage sorghum and corn was ensiled both years and analyzed for nutrient composition. This research suggests that forage sorghum silage may be an acceptable replacement for corn silage in areas with reduced irrigation capacities.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to think Dr. Vara Prasad for his guidance, knowledge and having the belief in me to continue my program when it was in peril. I appreciate the freedom and flexibility he has provided me and gave me the opportunity to expand my horizons beyond my own project. I have enjoyed being a part of his lab group and can't imagine doing it again without the Crop Physiology Lab. Dr. Prasad has been an excellent role model and shown me success at the next level is always possible.

I would like to thank Dr. Loyd Stone for giving his time and expertise and to serve as a member on my committee. Dr. Stone was able to give me the necessary tools for success in a project area I was new to. Dr. Stone shared his vast experiences in the soil water field that helped me understand and implement it into my project. I would also like to thank Dr. Stone for assisting me with my access to my neutron probe, I am very grateful for that and without his support the project would have suffered.

I would like to thank Dr. Evan Titgemeyer for his time and effort and serving as a committee member. I appreciated being able to stop by Dr. Titgemeyer's office and discuss research ideas in the animal science field that are out of my immediate expertise but know I can get closer to the answer I am looking for. I appreciate Dr. Titgemeyer's advice on the myriad of evaluations that were possible for plant biomass for my project. I would also like to thank Dr. Lorena Passarelli for being my outside committee chair.

I would like to thank Dr. Alan Schlegel for his time and expertise and serving on my committee. I would also like to thank Dr. Schlegel for hosting one of my research locations. Dr. Schlegel was part of the success of my project helping me with plot establishment and maintenance as well as a reliable source for agronomic data. I would also like to thank Dr.

Schlegel and his wife Martha for making me feel at home in their house during long research road trips.

Dr. Gerard Kluitenberg was instrumental in the completion of my project. Dr. Kluitenberg was kind enough to give me lab space, materials and guidance to complete the soil water retention part of my project. Dr. Kluitenberg has been a great resource for everything soils and as Graduate Program Director and is not afraid to answer my questions in the wee hours of the morning.

I would like to thank Dr. Lucas Haag for his friendship and guidance through my program. Dr. Haag and I have experienced 14 foot tall biomass in Doniphan County to 8 inch dryland cotton in Stevens County and drew line graphs on napkins in every restaurant in between. We have been through the rain, snow, sleet, wind, hail, tornados, flaming silage choppers and cotton strippers and tons of tall sorghum. Dr. Haag was the one who made me realize why research is important and that sometimes it takes a little more than what you have to get it done but it is worth it.

I would also like to thank Dr. Clenton Owensby for his guidance and direction during my graduate program here. Dr. Owensby was generous enough to allow me to help on the Rannells Research Prairie and teach me the finer points of grazing ecology. Dr. Owensby's expertise lent itself far beyond the pasture and helped me understand statistics and ruminant nutrition that helped complete my project. I would also like to thank the Range Management assistant scientist Lisa Auen. Lisa also gave me insight on statistics and research that helped me be successful in my program.

I would like to thank Kyle Shroyer and Scott Dooley for their help and guidance in the project. Scott Dooley was the man who introduced me to tall sorghum which would eventually become the purpose of my program here and has been a wealth of knowledge and has provided a lending hand in completing my field work. Kyle Shroyer has been a friend of mine since I started K-State 10 years ago. Kyle has been instrumental in providing me with statistics and research guidance and has always been willing to help.

I would not have gotten far in my project without the assistance of the assistant scientists, technicians and student technicians. I am very grateful for the help of the assistant scientists at the Tribune Experiment Station: Dewayne Bond, Jeff Slattery and Dale Nolan. I also owe a huge thanks to the student technicians who were instrumental in making everything us graduate students do here. They include Blake Bergkamp, Blake Nieheus, Keith Gustin, Christopher Maddy and Mary Kreikemeier at Manhattan.

I would like to thank my first major professor when I started my doctoral work and that is Dr. Scott Staggenborg. Dr. Staggenborg was instrumental in kick starting my doctoral work and gave me a foundation from which to work off. I appreciate Dr. Staggenborg's wealth of agronomic work and thoughts and views on agronomy.

I would to thank Scott Foote of Hoxie Feedyard of Hoxie, Kansas, for providing me with a location and necessary tools to have a successful plot location. I would like to thank Jeff Tourlemke of Hoxie, KS and his farm staff for providing me with assistance in establishing and maintaining my research location. I would like to thank Ed Heim at Hoxie Implement for his knowledge and assistance in the irrigation system that I used for my research. I would like to thank Vern Mowry of Hoxie for his assistance in plot maintenance and for providing me with a place to stay and work from in Hoxie.

I would like to thank the Sorghum Commission, K-State Research and Extension and the Ogallala Aquifer Program for making this research possible.

Dedication

This project is dedicated to my mother Donna, my father Robert , my sister Mallory and the love of my life Natalie who all have sacrificed more than I can pay back and shown love, support and patience as I complete this work, I couldn’t have done it without them.

I would also like to thank my heavenly father for giving the strength and patience necessary to complete this work. Evenin’ Lord…

Chapter 1 - Introduction

Ogallala Aquifer

With the world population increasing every year it is essential to be able to meet the food and fiber needs for a rapidly expanding population. Irrigation plays a vital role in sustainably intensifying agricultural lands for food production. Irrigation water sources are topics of debate in many regions around the world. In the High Plains Region of the United States lies the largest underground aquifer in the country. The Ogallala Aquifer is a regional system of freshwater that underlies eight states. The aquifer underlies an area approximately 450,000 km^2 ranging from Texas to South Dakota. The aquifer has a thickness ranging from less than 0.3 m to 396 m, with an average depth of 61 m (Peterson and Bernardo, 2003; High Plains Study Council, 1982). Gutentag et al. (1984) reported that due to over pumping, the Ogallala Aquifer has experienced reductions in water storage volumes and decreases in water table levels to as much as 150 feet. Approximately 30% of the groundwater used for irrigation in the U.S. comes from the Ogallala Aquifer and approximately 20% of the irrigated acres in the U.S. is in the High Plains region (Sophocleous, 2005; Gutentag et al., 1984). Over 90% of the water extracted from the aquifer is for irrigation (Ogallala Aquifer Management Advisory Committee, 2001). As advances in irrigation technology occurred through time such as the transition from flood irrigation to center pivot sprinklers and pumping technology advances, this allowed for continual exploration of possible irrigated acres of the aquifer (Green, 1990). Between 1959 and 1987, the irrigated acreage in all the High Plains states (including Texas, South Dakota, Nebraska, New Mexico, Wyoming, Oklahoma, Colorado and Kansas) increased by approximately 50% and in Kansas specifically it almost tripled (Lilienfeld and Asmild, 2007; Kromm and White, 1992).

There have been numerous efforts for water supplementation to the region such as increasing recharge through increasing filtration in basins (Aronovici et al., 1972) to interstate transfers and cloud seeding to increase precipitation (High Plains Associates, 1982; Lilienfeld and Asmild, 2007). These attempts have caused researchers to consider water use efficiency of crops to reduce water demand to increase the life of the aquifer (Kansas Water Office, 2001). Water use efficiency can be as easily calculated by unit of product per unit of water use (Tolk and Howell, 2003). Water use is the water consumed by the crop also called evapotranspiration (ET). ET can vary by crop and those values should be taken into consideration when evaluating management practices. In a study done by Hattendorf et al. (1988), water use was evaluated between corn, grain sorghum, pinto bean, sunflower, pearl millet and soybean and sunflower was shown to have a greater daily ET rate than the other five crops studied.

Issues arise when discussing irrigation and cropping systems. Water application efficiency is a topic of debate. Rogers et al. (1997) describes water application efficiency as the water delivered to the field per the water available to the crop. This is important to consider as flood irrigation systems can expect 50-90% efficiency, center pivot can expect 70-90% efficiency and drip systems can expect 75-95% water application efficiencies (Rogers et al., 1997). The location and topography of the area being irrigated also has to be considered. Plant available water capacity of the soil can be defined by the amount of water held in the soil between field capacity and permanent wilting point (Unger and Howell, 1999). When evaluating a particular location, available water content may depend on soil texture, soil profile depth and horizon characteristics (Unger and Howell, 1999; Tolk and Evett, 2012). Tolk and Evett (2012) found differences among different crops grown in different soil textures due to changes in available water capacity. This brings up the point of unused water when discussing irrigation. Lilienfeld and Asmild (2007) found that while irrigation systems may not strongly influence water use efficiency/water excess, but management techniques at the farm level play just as big of a role.

Research has been done to explore some of the ways to extend the life of the Ogallala Aquifer. Timing of irrigations can play a role in efficient water use. Stone et al. (1987) found that irrigating in the fall for the next year's summer crop may result in drainage losses and that irrigation water may be used more efficiently by applying in season. By understanding crop ET growers are better able to provide water to the crop when it is needed (Piccinni et al., 2009). Nielsen et al. (2005) found that transitioning from a conventional tillage system to a no tillage system, improving rotation schemes, cultivar selection and improving timing of crop production practices could cause an increase in available soil water and an increase in yield. Steward et al. (2013) note that irrigated corn follows ground water use and cattle production is focused around irrigated corn production for feed use. Steward et al. (2013) also noted that corn-fed cattle revenues far overshadow those from other agricultural sectors. With the importance of the Ogallala Aquifer and declining water levels on irrigated corn which is then important to cattle revenues, other avenues of feed production need to be explored to maintain economic stability in the region.

Corn

Corn (*Zea Mays* L.) is a C4 pathway crop and is adapted for summer growing conditions in the U.S. Corn is a member of the grass family *Poaceae*. Corn growth stages are driven by accumulated heat units. Corn is grown in most states with the bulk of the production in the Midwest. There were 90.5 million acres of corn in the U.S. in 2014 with an average yield of 171.0 bushels per acre and 20.1 tons per acre of corn silage (NASS, 2014). In 2014, Kansas harvested 3,950,000 acres of corn that averaged 149 bushels per acre and 14.0 tons of sorghum silage per acre (NASS, 2014).

Corn is responsible for around 50% of irrigated acres and most of the ground water pumped from the Ogallala Aquifer is used for irrigation (Schlegel et al., 2012; KSDA 1997). The High Plains have a high evaporative demand environment, with limited rainfall (Howell et al. 1997). Corn production systems that are successful in one location may not be successful in another due to a number of variables (Tolk et al., 1998). Researchers reported a maximum full season corn grain yield for the Pullman soil of 975 g m^{-2}, which was produced with 400 mm of irrigation, 230 mm of precipitation, and 667 mm ET (Tolk et al., 1998; Musick and Dusek, 1980). The same researchers in the same experiment noted the treatment that received 80 mm of irrigation produced no yield with 391 mm ET. At the same location, another researcher achieved 1550 g m^2 corn grain yield with 644 mm of irrigation, 227 mm of precipitation, and 973 mm of ET in a different cropping year (Tolk et al., 1998; Howell et al., 1995). The researchers had described the climate as near normal, with grain water use efficiencies that were similar. In a study done by Tolk et al. (1998) it was found that ET varied in corn based on soil type differences. Olsen (1971) notes that final yield does not necessarily depend on the total amount of water used, because yield is a function of not only the amount of water used during the growing season but also rainfall distribution, temperature and other factors.

Stress can be a major limiting factor in corn yields. Researchers found that stress at vegetative stages could reduce yields by 25%, stress at silking could reduce yields by 50% and stress after silking could reduce yields by 21% (Norwood, 2000; Denmead and Shaw, 1960). Corn appears to be the most susceptible to drought stress during pollination which can reduce seed number (Herrero and Johnson, 1981). Drought after pollination may limit the growth phase of kernel development and reduce kernel weight by reducing assimilation or duration (Lorens et al., 1987; Tollenaar and Daynard, 1978; Jurgens et al., 1978; Jones and Simmonds, 1983). Irrigation can help to mitigate drought stress imposed upon corn. Corn has been shown to respond to irrigation by many researchers. Corn yield was shown to increase with responses up to 0.05 Mg/ha-mm (Lamm et al., 2007). Schlegel et al. (2012) found that grain yield increased 28% by increasing the irrigation capacity from 2.5 to 5.0 mm d^{-1}. Howell et al. (2008) did a two year study to evaluate the ET of corn and found in 2006 the ET was 418 mm, the yield was 1,519 g m^{-2} and a water use efficiency (WUE) of 3.63 kg m^{-3}, and in 2007 the ET was 671 mm, the yield was 2, 444 g m^{-2} and the WUE was 3.64 kg m^{-3}.

Photosynthetically active radiation (PAR) is also a key ingredient in yield. Researchers found that under well-watered conditions and ample nutrition, in the absence of pests and diseases, corn yield has been shown to be closely related to the amount of radiation intercepted by the crop (Muchow et al., 1990; Loomis and Williams, 1963; Tollenaar and Bruulsema, 1988; Muchow 1989). Muchow et al. (1990) found that under favorable growing conditions, biomass accumulation is directly proportional to the amount of radiation intercepted. Researchers have found that there can be variations on the efficiency of the plant to be able to convert solar radiation into plant biomass which can be related to crop variety and crop development (Tollenaar and Bruulsema, 1988). Williams et al. (1968) noted corn approached physiological maturity when interception of PAR started to decline as grain fill is finishing. Solar radiation use as a determinate of yield becomes difficult as you move into a stressful environment with more limiting factors.

A study done by Miron et al. (2007), illustrated the difference between corn silage and sorghum silage. The research showed corn silage yielded better than the selected sorghum varieties and the corn also had more crude protein but an equal digestion rate as a brown midrib sorghum variety in the study. The study concluded that the higher yielding corn with similar digestibility was recommended versus the selected forage sorghums.

Forage sorghum

Forage sorghum (*Sorghum bicolor* (L.) Monech) is a C4 pathway crop grown as a summer annual in the U.S. Forage sorghum is a member of the grass family *Poaceae*. Sorghum is well suited to semi-arid conditions given its high water use efficiency (Rooney et al., 2007). Sorghum can be placed into multiple classes with forage being the one of focus (Dahlberg, 2000) for my research. Forage sorghums tend to be taller, leafier and have less grain than grain sorghums (Bean et al., 2013). Photoperiod sensitive sorghums (PSS) varieties of forage types initiate flowering when day length decreases below a given level and some varieties have been shown to initiate flowering 100-120 days later than their normal flowering counterpart, and typically flower when the day length is around 12 hours and 20 minutes (Rooney and Aydin, 1999). PSS have been evaluated as a bioenergy crop due their concentrations of cellulose and hemicellulose that can be used for biofuel conversion (Sivakumar et al., 2010). Another unique characteristic about PSS is that they are efficient at producing biomass due to their ability to remain in vegetative growth late into the growing season (Hao et al., 2014; Perlack and Stokes, 2011; Marsalis and Bean 2010).

Howell et al. (2008) performed a study that compared forage sorghum versus corn for silage and found that forage sorghum achieved nearly equal water productivity as corn. Howell et al. (2008) also found that lower ET was the contributing factor to the water productivity, while growing less biomass than corn, the forage sorghum was able to do it with less water use. In contrast, Hao et al. (2014) found an increase in WUE was due to higher biomass production and not lower ET. In a study done by Enciso et al. (2015), it was found in a forage sorghum study with 4 irrigation treatments, the dryland forage sorghum had the highest water use efficiency. Enciso et al. (2015) reported dryland forage sorghum biomass yields range from 5.8 to 8.7 Mg ha^{-1} and irrigated forage sorghum biomass yields to range from 14.6 to 16.6 Mg ha $^{-1}$. In an irrigated study done by Bean et al. (2013) to evaluate the growth of brown mid rib forage sorghum (BMR), sorghum-sudan forage sorghum, photoperiod sensitive BMR, photoperiod sensitive sorghum sudan, and a standard forage sorghum, found that the photoperiod sensitive sorghum sudan was the highest yielding at 19.0 Mg ha^{-1}. Researchers in Texas have found that PSS yields more biomass with less water use than other forage sorghums and corn (McCollum et al., 2005). Lodging can become an issue with high yielding tall forage sorghums grown in a region with high wind speed (Bean et al., 2013; Baumhardt et al., 2002).

Forage sorghum has characteristics such as high yield potential, biomass composition, high water use efficiency, established production system and potential for genetic improvement that make it a good candidate to add to a cropping system needing biomass production (Enciso et al., 2015; Rooney et al., 2007). Sorghum is growing in popularity as a silage crop, due to its low water requirement, specifically lower than corn (Bean et al., 2013; Howell et al., 2008; Marsalis et al., 2009.). Feeding trials have indicated dairy cattle milk yields and feeder cattle weight gain from being fed selected sorghum cultivars have had similar results as being fed corn (Aydin et al., 1999; Grant et al., 1995; McCuistion et al., 2004; Oliver et al., 2004).

A challenge of forage sorghum silage harvesting is the high moisture contents and its production of effluent in the silage pile (Castle and Watson, 1973). It is recommended that moisture level at harvest for silage crops be between 65-70% moisture (Schroeder, 2004). Storing PSS varieties are more difficult than other sorghums because of their constant vegetative stage and high moisture content; there is an increased risk of silage spoiling or a large loss of dry matter (Savoie and Jofriet, 2003). Typical grain sorghums would be harvested at dough stage for ensiling. Forage sorghum containing grain is at a disadvantage when it comes to ensiling because of the indigestibility of the sorghum kernel but this can be remediated by rolling to get digestion levels similar to corn silage (Havilah and Kaiser, 1992).

Neutral detergent fiber (NDF) represents the hemi cellulose in the plant while acid detergent fiber (ADF) represents the cellulose and lignin fractions (Bean et al., 2013; NRC 2001). NDF and ADF are values that help predict the digestibility of the forage. BMR forages are typically more digestible due to lower lignin content than other forage sorghums (Casler et al., (2003).

References

Aronovici, V.S., A.D. Schneider, and R. Jones. 1972. Basin recharge of the Ogallala Aquifer. J. Irr. Drain. Div. 98:65-76.

Aydin, G., R.J. Grant, and J. O'Rear. 1999. Brown midrib sorghum in diets for lactating dairy cows. J. Dairy Sci. 82:2127-2135.

Baumhardt, R.L., R.C. Schwartz, and R.W. Todd. 2002. Effects of taller wheat residue after stripper header harvest on wind run, irradiant energy interception and evaporation. In: E. van Santen. (Ed.), Proc. 25th Annual Southern Conservation Tillage Conference for Sustainable Agriculture. Alabama Agric. Exp. Sta. Spec. Rpt. No. 1. Auburn. AL, June 24-26, 2002, pp. 386-391.

Bean, B.W., R.L. Baumhardt, F.T. McCollum III, and K.C. McCuistion. 2013. Comparison of sorghum classes for grain and forage yield and forage nutritive value. Field Crops Res. 142:20-26.

Casler, M.D., J.F. Pedersen, and D.J. Undersander. 2003. Forage yield and economic losses associated with the brown-midrib trait in sudangrass. Crop Sci. 43:782-789.

Castle, M.E. and J.N. Watson. 1973. The relationship between the DM content of herbage for silage making and effluents production. J. Br. Grassl. Soc. 28:135-138.

Dahlberg, J., 2000. Classification and characterization of sorghum. In: C.W. Smith and R.A. Frederiksen, (Eds.), Sorghum: Origin, History, Technology, and Production. John Wiley & Sons, Inc., New York, NY, pp. 99-130.

Denmead, O.T. and R. H. Shaw. 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. 89:375-379.

Enciso, J., J. Jifon, L. Ribera, S.D. Zapata, and G.K Ganjegunte. 2015. Yield, water use efficiency and economic analysis of energy sorghum in South Texas. Biomass Bioenergy. 81:339-344.

Grant, R.J., S.G. Haddad, K.J. Moore, and J.F. Pederson. 1995. Brown midrib sorghum silage for mid-lactation dairy cows. J. Dairy Sci. 78:1970-1980.

Green, D. 1990. A history of irrigation technology used to exploit the Ogallala Aquifer. In; Kromm, D.E., S.E. White. Groundwater exploration in the High Plains. University Press of Kansas, Lawrence. pp. 28-43.

Gutentag, E.D., F.J. Heimes, N.C. Krothe, R.R. Luckey, and J.B. Weeks. 1984. Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming. U.S. Geological Survey, Professional Paper 1400-B, USGS, Reston, VA, 63 pp.

Hao, B., Q. Xue, B.W. Bean, W.L. Rooney and J.D. Becker. 2014. Biomass production, water and nitrogen use efficiency in photoperiod-sensitive sorghum in the Texas High Plains. Biomass Bioenergy. 62:108-116.

Hattendorf, M.J., M.S. Redelfs, B. Amos, L.R. Stone, and R.E. Gwin Jr. 1988. Comparative water use characteristics of six row crops. Agron J. 80:80-85.

Havilah, E.J., A.G. Kaiser. 1992. Sorghums for silage: a review. AIAS-Occasional publication. In: Proceeding of the 2nd Australian sorghum conference, Gatton, Queensland, Australia. 68:338-354.

Herrero, M. P., and R.R. Johnson. 1981. Drought stress and its effects on maize reproductive systems. Crop Sci. 21:105-110.

High Plains Associates. 1982. Six state High Plains – Ogallala Aquifer Regional Resources Study, Report to the U.S. Department of Commerce and the High Plains Study Council. High Plains Associates, Austin TX.

Howell, T.A., J.L. Steiner, A.D. Schneider, S.R. Evett and J.A. Tolk. 1997. Seasonal maximum daily evapotranspiration of irrigated winter wheat, sorghum and corn: Southern High Plains. Trans. ASAE 40:623-634.

Howell, T.A., S.R. Evett, J.A. Tolk, K.S. Copeland, P.D. Colaizzi, and P.H. Gowda. 2008 Evapotranspiration of corn and forage sorghum for silage. Wetting Front Newsletter. 10:1.

Jones, R.J. and S.R. Simmons. 1983. Effect of altered source-sink ratio on growth of maize kernels. Crop Sci. 23:129-134.

Jurgens, S.K., R.R. Johnson, and J.S. Boyer. 1978. Dry matter production and translocation in maize subjected to drought during grain fill. Agron. J. 70:678-682.

Kansas Water Office. 2001. http://www.kwo.org/Reports/Reports/ogallala_mac_rpt.pdf.

Kromm, D. E., and S. E. White. 1992. The High Plains Ogallala Region. In: Kromm, D.E., S.E. White. Groundwater exploitation in the High Plains. University Press of Kansas, Lawrence. pp. 1-27.

Lamm, F.R., L.R. Stone and D.M. O'Brien. 2007. Crop production and economics in Northwest Kansas, as related to irrigation capacity. App. Eng. Agric. 23:737-745.

Lilienfeld, A. and M. Asmild. 2007. Estimation of excess water use in irrigated agriculture: A data development analysis approach. Agric. Water. Manag. 94:73-82.

Loomis, R.S., and W.A. Williams. 1963. Maximum crop productivity: An estimate. Crop Sci. 3: 67-72.

Lorens, G.F., J.M. Bennett, and L.B. Loggale. 1987. Differences in drought resistance between two corn hybrids. II. Component analysis and growth rates. Agron. J. 79:808-813.

Marsalis, M.A., and B.W. Bean. 2010. Western forage production guide. Lubbock, TX, USA: United Sorghum Checkoff Program; http://amarillo.tamu.edu/files/2010/11/westernforageguidefinal.pdf

Marsalis, M.A., S. Angadi., F.E. Contreras-Govea, and R.E. Kirksey. 2009. Harvest timing and by product addition effects on corn and forage sorghum silage grown under water stress. Bull. 799. NMSU Agric. Exp. Stn. Las Cruces, NM.

McCollum, T., K. McCuistion and B.W. Bean. 2005. Brown midrib and photoperiod-sensitive forage sorghum. In: Proceedings of the 2005 Plains Nutrition Spring Conference; 2005 Apr. 14-15; San Antonio, TX, Amarillo, TX, USA: Texas A&M Univ. Ag. Res. and Ext. Center. pp 36-46.

McCuistion, K.C., F.T. McCollum, B.W. Bean, and M.W. Rowland. 2004. Observations on nutritional value of forage sorghums for silage. In: Swingle, S. (Ed.), Proc. Of the Plains Nutriton Council Spring Conference. San Antonio,TX, p. 105.

Muchow, R.C. 1989. Comparative productivity of maize, sorghum, and pearl millet in a semi-arid tropical environment. I. Yield potential. Field Crop Res. 20:191-205.

Muchow, R.C., T.R. Sinclair, and J.M. Bennett. 1990. Temperature and solar radiation effects on potential maize yield across locations. Agron. J. 82:338-343.

Musick, J.T. and D.A. Dusek. 1980. Irrigated corn yield response to water. Trans. ASAE 23:92-98,103.

NASS. 2014. National Agricultural Statistics Service. http://www.nass.usda.gov.

Nielsen, D.C., P.W. Unger and P.R. Miller. 2005. Efficient water use in dryland cropping systems in the Great Plains. Agron J. 97:364-372.

Norwood, C. 2000. Water use and yield of limited-irrigated and dryland corn. Soil Sci. Am. J. 64:365-370.

NRC (National Research Council). 2001. Nutrient Requirements of Dairy Cattle: Seventh Revised Edition. National Academies Press, Washington, D.C.

Ogallala Aquifer Advisory Committee. 2001. Discussion and recommendations for long-term management of the Ogallala Aquifer in Kansas. Topeka, Ks. Kansas Water Office.

Oliver, A.L. R. J. Grant, J.F. Pedersen and J. O'Rear. 2004. Comparison of brown midrib-6 and -18 forage sorghum with conventional sorghum and corn silage in diets of lactating dairy cows. J. Dairy Sci. 87:637-634.

Olsen, T. 1971. Yield and water use by different populations of dryland corn, grain sorghum and forage sorghum in the Western Corn Belt. Agron. J. 63:104-106.

Perlack, R.D., and B.J. Stokes. 2011. U.S. billion-ton update: biomass supply for a bioenergy and bioproducts industry. Oak Ridge, TN. Oak Ridge National Laboratory. Aug. p. 227. ORNL/TM-2011/224.

Peterson, J. M. and D. J. Bernardo. 2003. High Plains Regional Aquifer Study revisited: A 20-year retrospective for Western Kansas. Great Plains Res. 13:179-197.

Piccinni, G., J. KO, T. Marek, and T. Howell. 2009. Determination of growth stage specific crop coefficients (K_c) of maize and sorghum. Agric. Water Manag. 96:1698-1704.

Rogers, D., F.R. Lamm, M. Alam, T.P. Trooien, G.A. Clark, P.L. Barnes, and K. Mankin. 1997. Efficiencies and water losses of irrigation systems. Irrigation Management Series MF – 2243. Cooperative Extension, Kansas State University, Manhattan.

Rooney, W.L., and S. Aydin. 1999. Genetic control of a photoperiod-sensitive response in *Sorghum bicolor* (L.) Monech. Crop Sci. 39:397-400.

Rooney, W.L., J. Blumenthal, B. Bean, and J.E. Mullet. 2007. Designing sorghum as a dedicated bioenergy feedstock, Biofuels Bioprod. Biorefin. 2:147-157.

Savoie, P, and J.C. Jofriet. 2003. Silage storage. In: Buxton, D.R., R.E. Muck, and J.H. Harrison (Eds.), Silage Science and Technology. American Society of Agronomy, Inc., Crop Science Society of America, Inc, Soil Science Society of America, Inc, Madison, WI. pp. 405-467.

Schlegel, A.J., L.R. Stone, T.J. Dumler, and F.R. Lamm. 2012. Managing diminished irrigation capacity with preseason irrigaton and plant density for corn production. Trans. ASABE. 55:525-331.

Schroeder, J.W. 2004. Silage fermentation and preservation. AS-1254. NDSU Extension Service, Fargo, ND.

Sivakumar, G., D.R. Vail, J.F. Xu, D.M. Burner, J.O. Lay Jr, and X.M. Ge. 2010. Bioethanol and biodiesel: alternative liquied fuels for future generations. Eng Life. Sci. 10:8-18.

Sophocleous, M. 2005. Groundwater recharge and sustainability in the High Plains aquifer in Kansas, USA. Hydrogeol J. 13:351-65.

Steward, D.R., P.J. Bruss, X. Yang, S.A. Staggenborg, S.M. Welch and M. D. Apley. 2013. Tapping unsustainable groundwater stores for agricultural production in th High Plains Aquifer of Kansas, projections to 2110. Proc. Nat. Aca. Sci. 110:3477-3486.

Stone, L.R., R.E. Gwin, Jr., P.J. Gallagher, and M. J. Hattendorf. 1987. Dormant-season irrigation: Grain yield, water use and water loss. Agron. J. 79:632-636.

Tolk, J. A., and T. A. Howell. 2003. Water use efficiencies of grain sorghum grown in three USA southern Great Plains soils. Agric. Water Manage. 59:97-111.

Tolk, J.A. and S. E. Evett. 2012. Lower limits of crop water use in three soil textural classes. Soil Sci. Soc. Am. J. 76:607-616.

Tolk, J.A., T. A. Howell, and S.R. Evett. 1998. Evapotranspiration and yield of corn grown on three high plains soils. Agron. J. 90:447-454.

Tollenaar, M., and T.B. Daynard. 1978. Kernel growth at two positions on the ear of maize (Zea mays). Can. J. Plant Sci. 58:189-197.

Tollenaar, M., and T.W. Bruulsema. 1988. Efficiency of maize dry matter production during periods of complete leaf area expansion. Agron. J. 80:580-585.

Unger, P.W., and T.A. Howell. 1999, Agricultural water conservation-a global perspective. J. Crop Prod. 2:1-36.

Williams, W.A., R.S. Loomis, W.G. Duncan, A. Dovrat, and F. Nunez. 1968. Canopy architecture at various population densities and the growth and grain yield of corn. Crop Sci. 8: 303-308.

Chapter 2 - Evaluation of Corn and Forage Sorghum Production Tribune, Kansas.

Introduction

Underneath the U.S Great Plains lies the Ogallala Aquifer which supplies water for approximately 30% of all U.S. irrigation (Dennehy, 2000). The saturated thickness of the Ogallala Aquifer has been declining primarily due to irrigation in Kansas and Texas. (McGuire, 2004). Irrigated corn as feed and cattle production follows groundwater use patterns (Steward 2013). In past years, corn has been the main crop used for silage and roughage sources, but corn is considered a high water use crop that contributes to the extraction of Ogallala Aquifer water (McCuistion et al., 2009). McCuistion et al. (2009) found that in even reduced irrigation schemes, forage sorghum may be an alternative roughage crop. Poor irrigation management strategies are a major contributor to water shortages (Al-Kasi, 1997). With declining water levels producers should make efforts on improving water use efficiency of their cropping system (Stone 2006). Corn can be very responsive to irrigation and can yield up to 0.05 Mg/ha-mm or higher in the High Plains (Lamm, 2007). The definition of yield potential is described by the yield of a crop cultivar when grown in an adapted environment with all stresses controlled and water and nutrients being non-limiting (Evans, 1993). With more fields being subjected to a restricted amount of water instead of non-limiting as it was in the past, it is important to evaluate the water use efficiency of a crop and that may be a viable approach to increase water productivity (Condon et al., 2004).

Managers can manage declining pumping capacities by (1) growing crops that match the water supply, (2) reducing the irrigated acres and substituting fallow periods and dryland crops

(Martin et al., 1989; Klocke et al., 2006). Crop yield response has been measured for many years and researchers continue to study the effect because of the continued change in genetics and cropping systems (Klocke, 2011). On average, 85% of water use in Kansas is for irrigation (KWO, 2011). Final yield of both corn and sorghums is not solely dependent on the total water used because yield is a complex function of multiple factors such as rainfall amount and distribution, temperature and management decisions (Olson, 1971).

Sorghum is gaining attention as a key forage crop because of its drought tolerance and high productivity (Sanchez et al., 2002). Forage sorghums, unlike grain sorghums, have been developed for vegetative growth and maximum biomass production where grain sorghums have been selected for less vegetative growth and more grain yield (Bean et al., 2013). Sorghum cultivars can be separated in several types with two of those types being grown for grain and those grown for forage (Dahlberg, 2000) Photoperiod sensitive sorghum has been shown to be very efficient at producing vegetative biomass throughout the growing season (Marsalis et al., 2010). Forage sorghum has been found to have higher water use efficiency for producing biomass than corn (Olson, 1971, Rooney et al., 2007). Water use efficiency at the simplest level can be described as the crop yield per unit of water use (Sinclair, 1984).

Photoperiod sensitive sorghum in particular has been found to have higher biomass yields than headed forage sorghum with less water required (McCollum et al., 2005). When grown at different irrigation levels, it was found that photoperiod sensitive sorghum biomass yield, ET, water use efficiency, and irrigation water use efficiency were affected by irrigation (Hao et al., 2014). Howell et al. (2008) found that forage sorghum has 27% lower evapotranspiration than corn. At similar evapotranspiration rates, corn uses more water than sorghum because of earlier planting dates and a longer growing season (Howell et al., 1997). McCuistion et al. (2010) found that forage sorghum nutritional characteristics are similar to corn though quality decreased as yield and irrigation level increased.

There are other nutritional issues that exist with forage sorghum. Aydin et al. (1999) found that lignin concentrations in conventional forage sorghum limit dry matter intake and milk production. Forage sorghum was found to have lower in vitro dry matter digestibility than corn (Miron et al., 2007). In a study done by Marsalis et al. (2010) corn and forage sorghum may produce similar dry matter when harvested at optimum stage under restricted irrigation, corn will retain better nutritive value; and corn's ability to yield similar to forage sorghum under restricted irrigation is dependent upon in-season irrigation and that the high yields of corn in the study were due to above average precipitation. Corn silage harvest has a wide window of opportunity and research suggests that a harvest from blister to physiological maturity has no effect on intake by cattle of the silage (Johnson et al., 1968).

Environmental conditions control growth of the plant. Solar radiation is crucial for providing energy for evapotranspiration and the photosynthesis processes, including carbohydrates partitioning and biomass growth where air temperature regulates developmental rates of the plant (Boote and Loomis, 1991). Water deficits can cause significant growth and development issues. Decreasing soil water levels can reduce stomatal conductance, photosynthetic rates, transpiration and dry matter accumulation (Turner, 1974). Decreasing soil water was also found to negatively affect sorghum stem height, cumulative leaf area, leaf area indices and biomass production (Rosenthal, 1987). Arkin et al. (1987) found that decreasing soil water causes reduced leaf numbers, rate of individual leaf emergence from the whorl, leaf extension, and the senescence of sorghum.

Objective

It is understood that forage sorghum can be competitive with corn for forage use in western Kansas. Biomass production, water use efficiency and feed value of both crops have been considered as decision making factors for producers interested in forage production. An evaluation of corn alongside photoperiod sensitive forage sorghum may give some insight on forage production that is most efficient for western Kansas. The purpose of this study was to agronomically evaluate biomass production, water use and also understand basic feed values that can be used for further decision making.

Materials and Methods

Site data

A field study was conducted at the Kansas State University Southwest Research-Extension Center near Tribune, Kansas in 2011, 2012 and 2013. The soil is a deep silt loam soil (Ulysses silt loam; fine-silty, mixed, superactive, mesic Aridic Haplustolls). The average summer precipitation for the region is 353 mm. The study was a randomized complete block design with 4 replications. Plots were approximately 20 m long and 6 m wide (eight 76 cm rows). An irrigated treatment and dryland treatment were applied to corn and photoperiod sensitive forage sorghum (PSS). The corn was planted on 5 May 2011, 3 May 2012 and 6 May 2013. The corn variety was Pioneer 35F48 (Du Pont) and was planted at a density of 45,000 plants ha^{-1} for dryland plots and 79,000 plants ha^{-1} for irrigated plots. The forage sorghum was planted 3 June 2011, 30 May 2012 and 24 May 2013 and the variety was 1990 (Sorghum Partners) and was planted at a density of 99,000 plants ha^{-1} for dryland plots and 173,000 plants ha^{-1} for irrigated plots. Pre-emergence herbicides were applied to all treatments for weed control. Plots were irrigated with a linear-move sprinkler irrigation system with the capability to accommodate randomization of plots. Growing degree days (GDD) were calculated with an upper temperature threshold of 30°C for corn and 38°C for forage sorghum using a base temperature of 10°C (McMaster and Wilhelm, 1997). The initial position of the GDD line on Figure 2-2, 2-3 and 2-4 is the initial accumulation of GDD after planting.

Harvest and material handling

One meter of row (0.762 m^2) above ground biomass harvests were taken five times over the growing season (Table 2-1). Plants in a randomly selected linear meter of row were harvested 3-6 cm above the soil surface. Biomass was then dried at 60°C for 10 days and weighed. On the last day of harvest corn ears were separated from the stalk, mechanically shelled, dried at 60°C for a minimum of 72 hours and weighed. Grain yield was adjusted to 0.155 g g^{-1} moisture (wet basis). Total biomass was reported as sum of the stover, cob and grain on a dry matter basis. Harvest index was calculated by dividing dry grain yield by total dry above ground biomass. A fresh sample was taken to a laboratory (Servi-Tech Labs, Dodge City, KS) the day of harvest for nutrient analysis. Samples at the lab were dried and then ground. Crude protein content was taken using methodology found in AOAC (2012). Acid detergent fiber was evaluated according to Ankom (2006). Neutral detergent fiber was evaluated according to Ankom (2006). Nitrate content was taken using methods described by Cataldo et al. (1975). Prussic acid was taken using methods described by Gillingham et al. (1969).

Soil water

Soil volumetric water content was measured to a depth of 1.83 m using neutron probe (Model 503 DR, CPN International., Martinez, CA). Measurements were taken from 15 through 183 cm with probe activity centered on 0.3 m depths. Probe access tubes were installed in the center of each plot and attention was given to height of tube above the soil surface so that all measurements were taken at the same depth. Raw neutron counts were converted to neutron count ratio which is calculated by dividing raw neutron counts by a standard count given by the probe each time neutron probe readings are taken. Neutron probe count ratio was then converted to soil water content by an existing calibration. Existing neutron probe calibration and unavailable water contents for the field location were previously attained (Schlegel, personal communication). Neutron probe count duration was 16 seconds. The supplied equation developed for probe calibration is as follows

Equation 1: $$Y=2.3803X - 0.07161$$

where the independent variable (X) is neutron probe count ratio and (Y) the dependent variable is soil water. The equation was developed to inches per foot, soil water content was then converted to mm per 30.5 cm. Neutron probe readings were taken at each biomass harvest. To attain a sampling depth of 183 cm, neutron access tubes were installed in the center of each plot and inserted to a depth of 300 cm so that there was no opportunity for the neutron probe to come into contact with soil in the bottom of the access tube.

The soil profile was previously shown to have 277 mm of unavailable water (Schlegel, personal communication). Available profile water content was calculated as summing soil water contents at each depth minus unavailable soil water. Unavailable soil water is calculated as water that is unavailable below -1.5MPa. Seasonal water use was calculated by adding the soil water near planting less soil water at harvest plus total in season irrigation and precipitation minus drainage. Water use efficiency of biomass (WUE_b) was calculated as above ground biomass (kg ha-1) divided by seasonal water use (mm). Water use efficiency of corn grains (WUE_g) was calculated as dry corn grain (kg ha^{-1}) divided by seasonal water use (mm)

Drainage was calculated using a Wilcox-type drainage equation developed from Stone et al., (2001). The drainage equation was used to evaluate drainage at the 183 cm depth. Drainage was found in 2011. The range for total season drainage for irrigated corn plots was 0 to 48 mm and 0 to 50 mm for irrigated forage sorghum plots.

Light interception

Light interception data were collected with a LAI-2000 (LI-COR, Inc., Lincoln, NE) which recorded measurements from a 1 m line quantum sensor (Model LI-191SB, LI-COR, Inc., Lincoln, NE). Photosynthetically active radiation (PAR) was measured by placing the sensor perpendicular to the row, centered on the row, at the soil surface under the plant canopy. A measurement of incident PAR was taken immediately outside of the canopy. An inside the canopy and outside the canopy measurement was taken for each plot. Intercepted photosynthetically active radiation (IPAR) could then be calculated by dividing the below canopy measurement by the outside of the canopy measurement.

Data analysis

The experiment was a randomized complete block design with 4 replications. Data were analyzed using PROC MIXED in SAS (version 9.1, SAS Institute Inc., Cary, NC). Means and

and standard errors for corn grain were computed for all samples taken for each treatment and the respective LSDs were calculated. PROC GLM in SAS (version 9.1, SAS Institute Inc., Cary, NC) was used for linear regression.

Results

Weather

Long term precipitation and reference ET

Growing season precipitation for 2011, 2012 and 2013 is presented in Table 2-2. In 2012, monthly rainfall amounts were less than 2011 and 2013. In 2013, precipitation was higher than the long term mean while the 2012 precipitation was less than the long term average. The reference evapotranspiration (ET) is presented in Table 2-2 as a mean daily value during each month. Daily mean ET was greater in June, July and August during 2012 than 2011 and 2013. Temperature and precipitation were measured with an on site weather station. Long term weather data were extracted from the High Plains Regional Climate Centers web site (HPRCC). The daily ET values used for mean calculation were extracted from the Kansas State University Research and Extension Weather Data Library (KSUREWDL).

Average daily temperature

Average daily temperatures are presented in Figure 2-1. The highest average daily temperatures occurred in 2012 in July and August while 2013 saw cooler temperatures during the growing season. Daily maximum and minimum daily temperatures are presented in Appendix A-1, A-2 and A-3.

Growing degree days 2011

The figure for growing degree days (GDD) for 2011 in Tribune, Kansas, is presented in Figure 2-2. In 2011, corn showed accumulation of GDD earlier in the season than sorghum due to an earlier planting date. As the season progressed, sorghum quickly caught up with corn due to a higher maximum GDD equation growth temperature than corn. Corn silking initiated in late July into early August and physiological maturity happened around the middle of September.

Growing degree days 2012

The figure for GDD for 2012 in Tribune, Kansas, is presented in Figure 2-4. In 2012, corn accumulated GDD faster than sorghum due to an earlier planting date. Forage sorghum caught up and met or exceeded the corn GDD in the middle of September. Corn silking initiated in the middle of July and corn physiological maturity in the middle to late August.

Growing degree days 2013

The figure for GDD for 2013 is presented in Figure 2-5. In 2013, similar to the first two years, the corn accumulated GDD earlier in the growing season due to an earlier planting date. Sorghum accumulated GDD quickly due to higher maximum GDD equation growth temperature. Sorghum met and exceeded corn in GDD in early September. Corn silking initiated in the middle of July and physiological maturity in early September.

Irrigation

Irrigation was applied on several dates before and throughout the growing season. Monthly totals are presented in Table 2-3. Irrigation was applied early in the season to activate herbicide and help with germination and emergence in both irrigated and dryland plots.

Biomass and grain production

Biomass yields are presented in Table 2-4. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. In 2011, irrigated forage sorghum had higher biomass yields with 21.1 Mg ha^{-1} versus irrigated corn with 16 Mg

ha^{-1} total biomass. The dryland forage sorghum yielded similar to dryland corn with 11.1 and 11 Mg ha^{-1} respectively. Irrigated forage sorghum yielded 10 Mg ha^{-1}, 14.7 Mg ha^{-1} and 4.5 Mg ha^{-1} which was higher than dryland forage sorghum in 2011, 2012 and 2013 respectively. The year 2012 showed the only statistical difference in biomass yields in both irrigated and dryland treatments. Irrigated forage sorghum yields were greater with 20.8 Mg ha^{-1} of biomass versus irrigated corn with 9.8 Mg ha^{-1} (P=.002). The lower yields in 2012 in irrigated corn and both dryland treatments may be attributed to lower than average precipitation. The dryland forage sorghum yields were higher with 6.1 Mg ha^{-1} with dryland corn yields of 3.9 Mg ha^{-1} (P=.028). Yields in 2013 were similar to 2011 yields. The irrigated forage sorghum yield was 20.6 Mg ha^{-1} and irrigated corn produced 17.6 Mg ha^{-1}. The 2013 dryland forage sorghum yielded 16.1 Mg ha^{-1} and dryland corn yielded 11.6 Mg ha^{-1}.

Corn grain yields and corn harvest index are presented in Table 2-5. Corn grain yields in 2012 were lower than 2011 and 2013 and this was attributed to weather patterns. The large standard error suggests a larger sampling error than in 2012 and 2013. The highest grain yields were in the irrigated corn in 2013; this year had cooler temperatures than 2011 and 2012 and also had adequate rainfall and irrigation. The lowest observed grain yields were in the dryland corn plots in 2012. Harvest index represents the amount of grain as a part of the whole plant biomass.

Biomass accumulation for irrigated corn, irrigated forage sorghum, dryland corn and dryland forage sorghum in 2011 is presented in Figure 2-5. Irrigated corn accumulated biomass faster than any of the other treatments. This could be due to earlier planting than the forage sorghum and the advantage of irrigation. Irrigated forage sorghum, dryland corn and dryland forage sorghum accumulated biomass similarly until September when the corn started to mature and lose biomass and the irrigated and dryland forage sorghums continued to grow.

Biomass accumulation for irrigated corn, irrigated forage sorghum, dryland corn and dryland forage sorghum in 2012 is presented in Figure 2-6. In 2012, dryland corn and irrigated corn both accumulated biomass earlier than irrigated and dryland sorghum. Irrigated sorghum biomass accumulation rose above irrigated corn biomass accumulation in early August with dryland sorghum surpassing dryland corn biomass accumulation in the middle of August.

Biomass accumulation for irrigated corn, irrigated forage sorghum, dryland corn and dryland forage sorghum in 2013 is presented in Figure 2-7. In 2013, only irrigated corn and dryland corn were able to be harvested at each sampling period during the growing season due to poor irrigated and dryland sorghum stands. Irrigated and dryland forage sorghum were only able to be harvested at the last sampling date. Irrigated sorghum yielded higher than any of the other treatments and dryland forage sorghum yielded higher than any other year. The irrigated corn showed a dramatic increase in biomass accumulation versus dryland corn.

Soil water and water use efficiency

Available soil water by depth for 2011 is presented in Table 2-6. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. Statistically significant differences in available soil water occurred at each sampling date for the irrigated treatments; no statistically significant differences occurred in the dryland treatments. At the 1 July sampling date, significant differences occurred at the 30 and 61 cm sampling depths with irrigated forage sorghum having more available water at the 30 and 61 cm sampling depth than the irrigated corn. This can be attributed to earlier season growth of the corn. The 20 July sampling date showed significant differences at the 61 and 91 cm sampling depths with irrigated forage sorghum showing more available water than irrigated corn. The 3 August sampling date showed a significant difference at lower depths of 152 and 183 cm depths with irrigated sorghum having more available water than irrigated corn. The 23 August date again showed a significant difference at the 183 cm sampling depth. The 20 October sampling date showed a significant difference at the 30 cm depth, this coincided with the late season growth of photoperiod sensitive forage sorghum.

Available soil water by depth for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn for 2012 are presented in Table 2-7. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. Two statistical differences were observed in 2012. The 25 June sampling date showed a significant difference at the 30 cm depth with forage sorghum having slightly more available water at the 30 cm depth than irrigated corn. This could be attributed to the early season growth of the irrigated corn. There was also an observed difference at the 15 July sampling date with dryland forage sorghum having slightly more available water at the 122 cm depth than dryland corn.

Available soil water by depth for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn for 2013 is presented in Table 2-8. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. There were 3 sampling dates that showed statistical significance in 2013. The 10 July sampling date showed significance at the 30 cm depth with irrigated forage sorghum having more available water than irrigated corn. The 22 August sampling date showed significance at the 30 cm sampling depth with irrigated corn showing slightly more water than the irrigated forage sorghum. This date also showed a difference at the 122 cm sampling date with dryland forage sorghum having more water than dryland corn. The 26 September sampling depth showed significance with irrigated corn showing more water at the 30 and 61 cm sampling depth than irrigated forage sorghum. On the same sampling date dryland corn showed more available water than dryland forage sorghum.

Available soil water for the 183 cm profile for 2011 is presented in Table 2-9. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. Available soil water on 20 July for irrigated forage sorghum was significantly different than irrigated corn. There was also a significant difference on 3 August between irrigated forage sorghum and corn. Dryland corn ended the year with the most available water and irrigated forage sorghum had the least available water at the end of the year.

Available soil water for the 183 cm profile for 2012 is presented in Table 2-10. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. Though no significant differences were found for 2012, numerical differences did exist. The available soil water showed a dramatic decrease as the season progressed. The lowest available soil water amounts for any year existed on the 15 September sampling date.

Available soil water for the 183 cm profile for 2013 is presented in Table 2-11. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. Similar to 2012, no significant differences were found but numerical differences did exist. The soil profile was able to increase its water content from the last sampling date in

2012. Irrigated corn ended the season with the most available soil water and dryland forage sorghum had the least available soil water.

Total water use of irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn are presented in Table 2-12. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. In 2011, a significant difference was observed with irrigated forage sorghum having greater water use than irrigated corn. The opposite was observed in 2013, with irrigated corn using more water than irrigated forage sorghum. No statistically significant differences were observed in the dryland treatments.

Water use efficiency WUE of the biomass (WUE_b) of irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn is presented in Table 2-13. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. In 2012, significant differences exist between irrigated forage sorghum and irrigated corn with irrigated forage sorghum having a higher WUE_b than irrigated corn. Dryland forage sorghum also showed significantly higher water use efficiency than dryland corn in 2012. No statistically significant differences were found in 2011 and 2013.

The WUE_c of irrigated corn and dryland corn is presented on Table 2-14. Standard error was reported for each treatment by year. Irrigated corn grain water use efficiency (WUE_g) was highest in 2013 at 18 kg ha^{-1} mm^{-1} and lowest in 2012 with 9.44 kg ha^{-1} mm^{-1}. A large standard error exists in 2011 which can be attributed to sampling error. Dryland corn WUE_g was the highest of any corn treatment in 2013 at 20.01 kg ha^{-1} mm^{-1} and lowest in 2012 at 7.76 kg ha^{-1}

mm^{-1}. A large standard error also existed for the dryland corn treatment in 2013, due to sampling error.

Tribune biomass versus water use for 2011, 2012 and 2013 is presented in Figure 2-8. A linear regression was developed for this data. A liner regression equation was developed by using PROC GLM of SAS (version 9.1, SAS Institute Inc., Cary, N.C.) with water use (millimeters) the independent (X) variable and the biomass (kilograms per hectare) the dependent variable (Y). The biomass versus water use equation for forage sorghum is:

Equation 2 $$Y=3.32+0.025x,\ r^2=0.361$$

where sample size (n)=24, and coefficient of simple determination (r^2) = 0.361. The same equation was developed for corn and it is given as follows:

Equation 3 $$Y=3.22+0.017x,\ r^2=0.355$$

where sample size (n)=24, and coefficient of simple determination (r^2) = 0.355. The forage sorghum biomass accumulation slope shows a greater increase per unit of water than corn.

Light interception

Fraction of intercepted photosynthetically active radiation (IPAR) for irrigated forage sorghum, irrigated corn, dryland forage sorghum and irrigated corn for 2011 is presented in Table 2-15. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. A statistical difference was found in the irrigated treatment for the 1 July, 20 July, 23 August and 20 October sampling dates. The overall trend of the data for the irrigated treatment showed the intercepted solar radiation peaked sooner in the season for the irrigated corn than the irrigated forage sorghum. Irrigated forage sorghum showed the most IPAR during the 23 August sampling date. A statistical difference was found in the dryland treatments for the 23 August and 20 October sampling dates. In contrast to the irrigated treatments, the dryland treatment suggested an increased IPAR for dryland forage sorghum sooner in the season than dryland corn. Dryland forage sorghum also sustained higher IPAR through the end of the season versus a decrease through the end of the season for dryland corn.

Fraction of intercepted photosynthetically active radiation (IPAR) for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn for 2012 are presented in Table 2-16. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. All sampling dates except the 15 July sampling date in the irrigated treatments showed a significant difference. Irrigated corn increased in IPAR faster than irrigated forage sorghum while irrigated forage sorghum continued to maintain IPAR through the end of the season where corn decreased on the last sampling date. Dryland corn showed a similar trend in 2012, as the 2012 irrigated treatment, with dryland corn increasing earlier in the season and decreasing on the last sampling date versus the dryland sorghum that increased IPAR through the end of the season.

Fraction of intercepted photosynthetically active radiation (IPAR) for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn for 2013 are presented in Table 2-17. Irrigated forage sorghum and irrigated corn were analyzed separately from dryland forage sorghum and dryland corn. A significant difference was found in all but the 22 July sampling date for the irrigated treatments. Irrigated corn increased IPAR sooner in the season and then slowly decreased after 22 July. Irrigated forage sorghum increased IPAR later in the season and maintained IPAR through the end of the season. The dryland treatments followed a similar trend as the irrigated treatments and showed a significant difference for all sampling dates except 23 July. Both dryland forage sorghum and corn increased IPAR through the end of the season in 2013.

Nutrient values

Fraction of crude protein for forage sorghum and corn stover for 2012 and 2013 are presented in Table 2-18. Forage sorghum was analyzed separately from corn treatments. Irrigated forage sorghum has lower crude protein than dryland forage sorghum for both years of the study. Irrigated corn and dryland corn stover contains a similar amount of crude protein for both years of the study.

Fraction of acid detergent fiber (ADF) for irrigated forage sorghum and irrigated corn stover for 2012 and 2013 are presented in Table 2-19. Forage sorghum was analyzed separately than corn. In 2012, irrigated forage sorghum has a higher ADF value than dryland sorghum. Irrigated corn and dryland corn ADF values are similar in 2012 and irrigated corn has a higher ADF value in 2013.

Fraction of neutral detergent fiber (NDF) for irrigated forage sorghum and irrigated corn stover for 2012 and 2013 are presented in Table 2-20. Forage sorghum was analyzed separately than corn. Irrigated forage sorghum has a higher NDF value than dryland forage sorghum in both years of the study although the difference is small in 2013. Irrigated corn has a smaller

NDF value in 2012 than dryland corn. The opposite occurs in 2013, when irrigated corn had a higher NDF value than dryland corn.

Nitrates for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn for 2012 and 2013 are presented in Table 2-21. Forage sorghum was analyzed separately from corn. Irrigated forage sorghum had a higher nitrate concentration in 2012 and 2013 than dryland forage sorghum. Irrigated corn had a lower nitrate concentration in 2012 than dryland corn while irrigated corn had a greater nitrate accumulation in 2013 than dryland corn.

Prussic acid for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn for 2012 and 2013 are presented in Table 2-22. Forage sorghum was analyzed separately from corn. In 2012, dryland forage sorghum had more prussic acid than irrigated forage sorghum. In 2013, the opposite occurs when irrigated forage sorghum had more prussic acid than dryland forage sorghum. Though differences exist between irrigated corn and dryland corn, the values are small and not expected to cause issues with livestock.

Discussion

Biomass production

Evaluating above ground biomass was the initial goal of the research. Corn biomass accumulation started earlier in the spring due to an earlier planting date than forage sorghum, usually with a month difference. In 2011, irrigated forage sorghum biomass did not exceed irrigated corn biomass until after 1 October. In contrast, in 2012, irrigated forage sorghum exceeded irrigated corn biomass around the end of July. This difference was due to the stressful growing conditions in 2012, where rainfall was well below average and corn silking happened in a period of high temperatures. Researchers have found that stress at vegetation reduced yields by 25% and stress after silking reduced yields by 21% and reduction as high as 50% when stress occurs at silking (Denmead and Shaw, 1960). Dryland corn yields also suffered from stressful conditions in 2012. Irrigated forage sorghum had the highest yield of the 3 year study in 2011, which was also the year with the highest water availability which agrees with Yimam (2015) who in a three year study found the year with the greatest forage sorghum production was also the year with the highest rainfall. Dryland corn biomass yields were similar in 2011 and 2013. The dryland corn experienced good growing conditions in those years and biomass and yields agreed well with similar work done by Frank et al. (2013). In 2012, dryland corn and dryland forage sorghum yielded similar over time which was related to poor growing conditions. Irrigated forage sorghum yielded higher than dryland forage sorghum. Irrigated sorghum yielding higher than dryland sorghum was expected and observed by other researchers (Weichenthal et al., 2003; McCuistion et al., 2009). Irrigated forage sorghum yielded well in stressful conditions in 2012. This particular forage sorghum was a photoperiod sensitive plant that did not undergo reproductive heat and drought stress like corn and was more likely to not be affected as badly by stressful conditions. Corn grain yield mean for three study years was slightly lower at 9.5 Mg ha^{-1}, than a 10 year mean of fully irrigated corn reported by Schlegel and Havlin (1995) which was 11.1 Mg ha^{-1}. Corn grain yield was affected by the stressful conditions with a dramatically lower yield in 2012 than in 2011 and 2013. Harvest index numbers were higher than those reported by others (Olson, 1971). The harvest index values were high due to a longer period of time between physiological maturity and harvest. The plants were exposed to natural degradation and weathering.

Water use and water use efficiency (WUE) of biomass and grain production

Growing season water use ranged from 773 mm to 284 mm for forage sorghum, and 744 mm to 291 mm in corn. Water use values agreed with other researchers (Howell et al., 2008; Hao et al., 2014). Water use has varying effects on biomass production. Grain sorghum was found to achieve similar yields with varying levels of water use (Tolk and Howell, 2003). This could be the case with forage sorghum. This was shown possible by evaluating biomass production and water use for irrigated forage sorghum that showed consistent yields with water use ranging from 773 mm to 544 mm. Dryland forage sorghum had similar yields in 2011 and 2013, and two water use levels of 400 mm and 342 mm respectively. In 2011 and 2013, biomass yields were similar for irrigated corn with water use in 2011 being 744 mm and water use in 2013 being 581 mm. The highest water use of any treatment of any year was irrigated forage sorghum in 2011. Hao et al. (2014) found WUE_b values for forage sorghum ranging from 30 to 47 kg ha^{-1} mm^{-1}, which agrees with the study data. Corn WUE_b and WUE_g were in agreement with previous work done at Tribune (Hattendorf et al., 1988). Corn WUE_b values ranged from 34 kg ha^{-1} mm^{-1} to 13.4 kg ha^{-1} mm^{-1} which both occurred in the dryland treatment. A similar thing happened with WUE_g where the highest and lowest values for the study years were in the dryland treatments. The highest WUE_b and WUE_g yield occurred in the year with the least amount of water use. This data is in agreement with Tolk and Howell (2003) who said that on average, corn shows higher WUE and lower water use in mild weather conditions which is what was observed. Howell et al. (1995) also suggested in a separate study that WUE is generally maximized as water use declines. Dryland corn yields agreed with those of Norwood (2000). Dryland corn yields in 2011 and 2013 were similar with a difference in those years in water use, 2013 had a lower water use value which is what contributed to a higher WUE_b and WUE_g value than 2011. This also occurred with irrigated corn where higher biomass yields with less water use in 2013 gave a greater WUE_b for 2013 than 2011. In 2012, biomass production was low with a high water use value giving a lower WUE_b value for 2012 than 2011 and 2013. Dryland corn showed the highest WUE_g value in 2013, which could be attributed to mild growing conditions with the lowest WUE_g in 2012 which can be attributed to stressful growing conditions. The high standard error in irrigated corn in 2011 and dryland corn in 2013 came from sampling error. A common source of error of this experiment came from the low number of plant samples taken to represent a hectare. Figure 2-8 shows the forage sorghum and corn biomass versus water use plotted across 2011, 2012 and 2013. The slope shows forage sorghum accumulating more biomass per mm of water than corn. Forage sorghum accumulated 2.5 Mg ha^{-1} per 100 mm of water where corn accumulated 1.7 Mg ha^{-1} per 100 mm of water. Other researchers have found photoperiod sensitive sorghum to accumulate as high as 4.4 Mg ha^{-1} per 100 mm in Texas (McCuistion et al., 2009). The r^2 value for both crops are lower than those reported by McCuistion et al. (2009). This is largely explained by error in sampling and stressful growing conditions in 2012 severely reducing yield. When only sampling 0.762 m^2 of plot per harvest timing, it may not be sufficient to capture the real yield of plot.

Soil water

Available soil water content was not equal in quantity and timing but trends appeared. Differences appeared in 2011 early in the season in the irrigated corn and forage sorghum while dryland values were remained similar. The dryland soil profile had dropped in available soil water content between 1 July to 20 July due to increased growth during that time. Available soil water showed an increase in profile water at the 3 August sampling date due to rainfall. Available soil water for the 183 cm profile showed two significant differences at 7 July and 3 August which irrigated corn had less available water than irrigated forage sorghum which can be attributed to rapid growth rate (Figure 2-6) and initiation of silking for the irrigated corn (Figure 2-3). All treatments decreased in water from 1 July to 20 October due to more water use than what could be replenished as rainfall or irrigation.

In 2012, numerical differences did occur with depth, treatment and timing. Very little statistical significance appeared in 2011. There was a significant difference at 25 June with irrigated corn having slightly more available soil water than irrigated corn and this can be attributed to earlier growth of the irrigated corn. A trend that occurred in both the dryland and irrigated treatments was the drying down of the soil profile over time. This was due to below average rainfall and high water use by the irrigated corn and irrigated sorghum specifically. Table 2-10, shows a drastic reduction in plant available water from 12 June to 15 September. The largest decrease in available soil water was in the dryland treatments due to lower than average rainfall not being able to replenish soil water. The irrigated treatments showed considerable drying even with irrigation, water use demands were higher and the irrigated corn and irrigated forage sorghum were able to produce 9.8 and 20.8 Mg ha^{-1} of biomass respectively.

In 2013, similar to years prior, there were numerical differences between available soil water contents by depth, treatment and across sampling dates. There were four statistically significant differences to note. The irrigated corn on 10 July had slightly less water than irrigated forage sorghum with the cause being earlier growth of the irrigated corn versus the irrigated forage sorghum. This scenario changes later on in the season on 22 August and 26 September where irrigated forage sorghum had less available soil water than irrigated corn. This was due to irrigated corn approaching maturity and irrigated forage sorghum still in a growing vegetative stage. Available soil water for the 183 cm profile showed a decrease on profile available water from 25 June to 26 September designating crop water use and growing biomass.

Light interception

Light interception for 2011, 2012 and 2013 all show a trend for significant differences. In all years for irrigated treatments there is a significant difference in the first two sampling dates and the last two sampling dates. The non-significant date for each year was when forage sorghum had rapidly accumulated biomass and expanding leaf area and has similar leaf area as the corn. This sharply rising growth curve is most obvious in 2012. The significance of the first two sampling dates of every year relate to the fact that irrigated corn was planted earlier and was increasing in biomass and leaf area earlier than irrigated forage sorghum. The other interesting note about the significant differences was that the significant differences at the last date are due to the maturation and loss of leaves in the irrigated corn and forage sorghum was still increasing in biomass and still intercepting more than 90% of PAR. Dryland treatments also showed differences at the end of the growing season where dryland forage sorghum is still growing and intercepting over 88% of the PAR and corn has begun physiological maturation and due to senescence had started to decrease interception of PAR. The data tends to agree with Muchow et al. (1990) who found that under favorable growing conditions, biomass accumulation is directly proportional to the amount of radiation intercepted.

Nutritional values

Nutritional values were collected at the end of the season to get an idea of the nutritional quality of the plant material. Crude protein was evaluated because it is a common parameter in animal feed. Crude protein of the corn stover and forage sorghum was tested to determine what the differences where in just the vegetative material. There was a significant difference in 2012 between irrigated forage sorghum and dryland forage sorghum with dryland sorghum having a greater amount of crude protein. Dryland and irrigated corn crude values were similar in 2012 and 2013. The values for crude protein for forage sorghum tend to agree with McCuistion et al. (2010). Corn stover values are similar to that of Lauer et al. (2001).

Acid detergent fiber (ADF) was evaluated to determine the amount of cellulose and lignin that are difficult for digestion and have been shown to limit digestion (NRC, 2001). There was a significant difference in 2012 where the fraction of ADF in dryland forage sorghum was lower than irrigated forage sorghum. This difference could be attributed to stressful growing conditions. The difference in 2013 was much smaller. This implies that in 2012 irrigated forage sorghum had more cellulose and lignin fiber components than dryland forage sorghum. In 2012, dryland corn and irrigated corn were similar. Forage sorghum ADF values were in agreement with Cummings (1981) while corn ADF values agreed with Crasta et al. (1997).

Neutral detergent fiber (NDF) was evaluated to determine the amount hemi cellulose and other neutral detergent soluble components. Irrigated forage sorghum had significantly more NDF than dryland forage sorghum in 2012 that could be related to stressful conditions. The difference between irrigated forage sorghum and dryland forage sorghum in 2013 was small. A significant difference existed in 2013, where irrigated corn had significantly more NDF than dryland corn. Forage sorghum NDF values were similar to those found by McCuistion et al. (2010). Corn NDF values tended to agree with NDF values found by Cox et al. (1994)

Nitrates were evaluated to determine if toxic levels existed in the plant material. Numerical differences existed amongst all treatments. These levels are important to determine if livestock can be fed the plant material. Nitrates have been found to be toxic and fatal to livestock at high levels (Harms and Tucker, 1973). Animals have varying levels of sensitivity to nitrate levels in plant material. It is important to note the levels in the plant matter for feeding.

Prussic acid which is also known as hydrocyanic acid, was evaluated to determine if toxic levels of the compound existed. Though there were numerical differences an important significant difference was dryland forage sorghum had 690.5 mg/kg of prussic acid. This amount of prussic acid could be fatal to livestock (Egekeze and Oehme, 1980). Prussic acid has been shown to increase in stressful conditions (Wheeler et al., 1990).

Due to the nature of the research, corn was not able to be sampled on a representative date that it would be taken for corn silage. The corn samples taken represent a stover harvest. Samples taken to represent silage must also undergo an ensiling process to get a correct representation of the nutrients. The difference in nutritive values will change based on harvest date. Corn has an earlier maturity date than the photoperiod sensitive forage sorghum. Harvest date must be taken into consideration when evaluating nutritional values.

Conclusions

In Tribune, irrigated forage sorghum was able to produce more biomass than irrigated corn. Dryland forage sorghum was able to yield the same or higher as dryland corn. Final yield does not necessarily depend on the total amount of water used, because yield is a function of not only the amount of water used during the growing season, but also of rainfall distribution, temperature and other factors (Olsen, 1971). Though there were numerical differences, total water use between the irrigated forage sorghum and the irrigated corn were similar. This also happened with dryland plots; dryland forage sorghum used a similar amount of water as the dryland corn. Though the forage sorghum used more water it was able to produce more biomass with that water giving it higher water use efficiency than corn except in 2011, when the dryland corn had slightly higher water use efficiency than dryland forage sorghum. This is important in years with stressful growing conditions such as 2012. This year brought above average temperatures and below average rainfall and the sorghum was able to produce more biomass per unit of water than corn because it did not undergo reproductive stress in periods of high temperatures and its GDD equation states that the maximum growing temperature for sorghum is 37.7^{o}C versus 30^{o}C. Because the forage sorghum is photoperiod sensitive it is also allowed to grow later on in the growing season as seen by the biomass growth over the season and the PAR which shows sorghum is still intercepting 90% of the incoming solar radiation at the end of the season where corn is decreasing because it is drying down after physiological maturity. The producer needs to understand if their goals are for grain production or biomass production. In areas with declining well capacities with producers needing a fiber product for animals, forage sorghum has shown that it can produce just as much biomass as corn with a similar amount of water. The feed nutrition data suggest that though there is significance, the actual values give producers decision making tools to help them pick the right product for evaluation. To get a true value for what the plant material is worth as a feedstuff, feeding trials need to be established to understand the digestibility of the material and how it reacts within the rumen.

Table 2-1. Biomass harvest dates for Tribune, Kansas.

2011	2012	2013
1 July	12 June	25 June
20 July	25 June	10 July
3 August	15 July	22 July
23 August	29 July	22 August
20 October	15 September	26 September

Table 2-2 Long-term (100 yr) temperature and rainfall means by month, mean daily reference ET by month and rainfall by month for Tribune, Kansas 2011, 2012 and 2013.

	100-yr mean			Reference ET			Precipitation		
	Max	Min	Precipitation	2011	2012	2013	2011	2012	2013
	--^{o}C--		mm	--mm d^{-1}--			--mm--		
Apr	19.1	1.6	33.5	4.8	4.3	4.3	36.1	38.8	3.0
May	24.1	7.5	64.0	6.0	6.2	6.7	25.4	9.9	35.3
Jun	30.1	13.1	70.1	7.8	9.4	8.7	75.4	23.3	36.8
Jul	33.5	16.1	66.3	7.6	9.3	7.3	116.8	20.5	58.9
Aug	32.1	15.2	59.9	6.2	7.3	5.9	117.3	20.3	136.1
Sep	27.7	10.1	32.2	4.2	5.3	5.4	25.1	26.9	37.3
Oct	21.2	2.9	27.4	3.4	3.3	3.4	76.4	24.1	19.3
Total			353.4				472.7	188.7	326.9

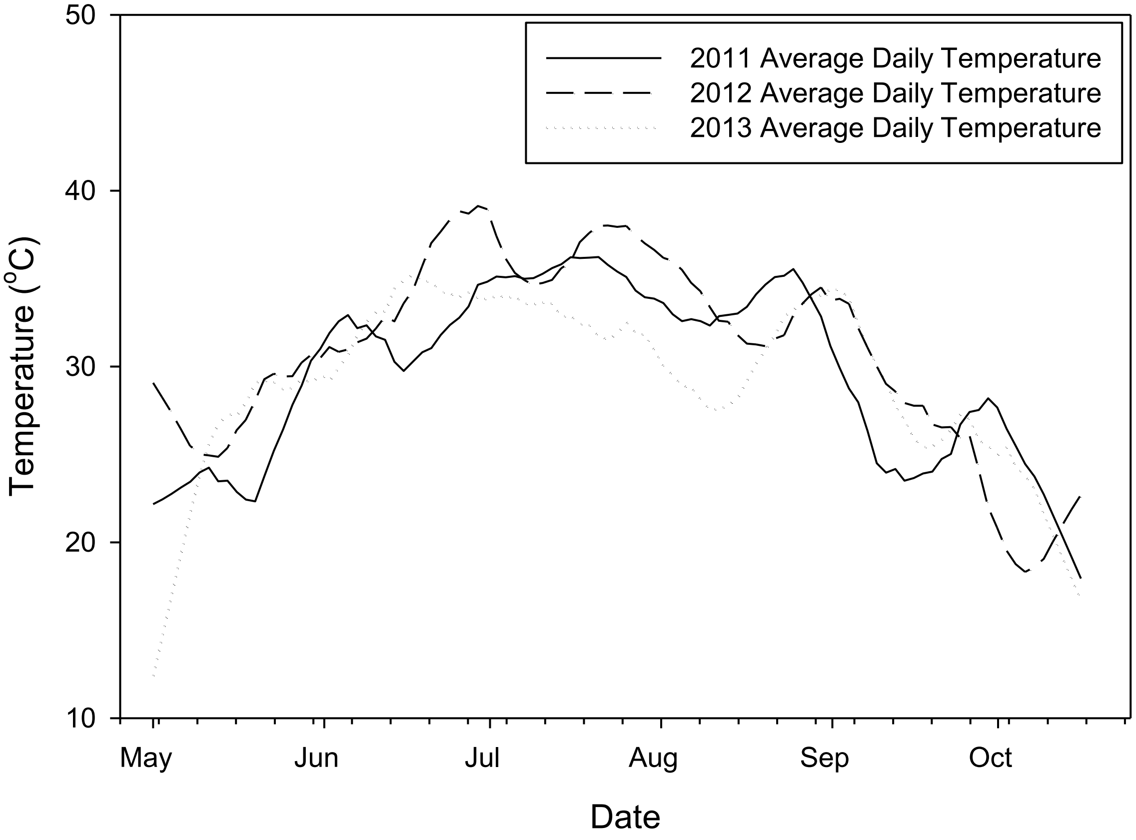


Figure 2-1. Average daily temperature for Tribune, Kansas 2011, 2012 and 2013.

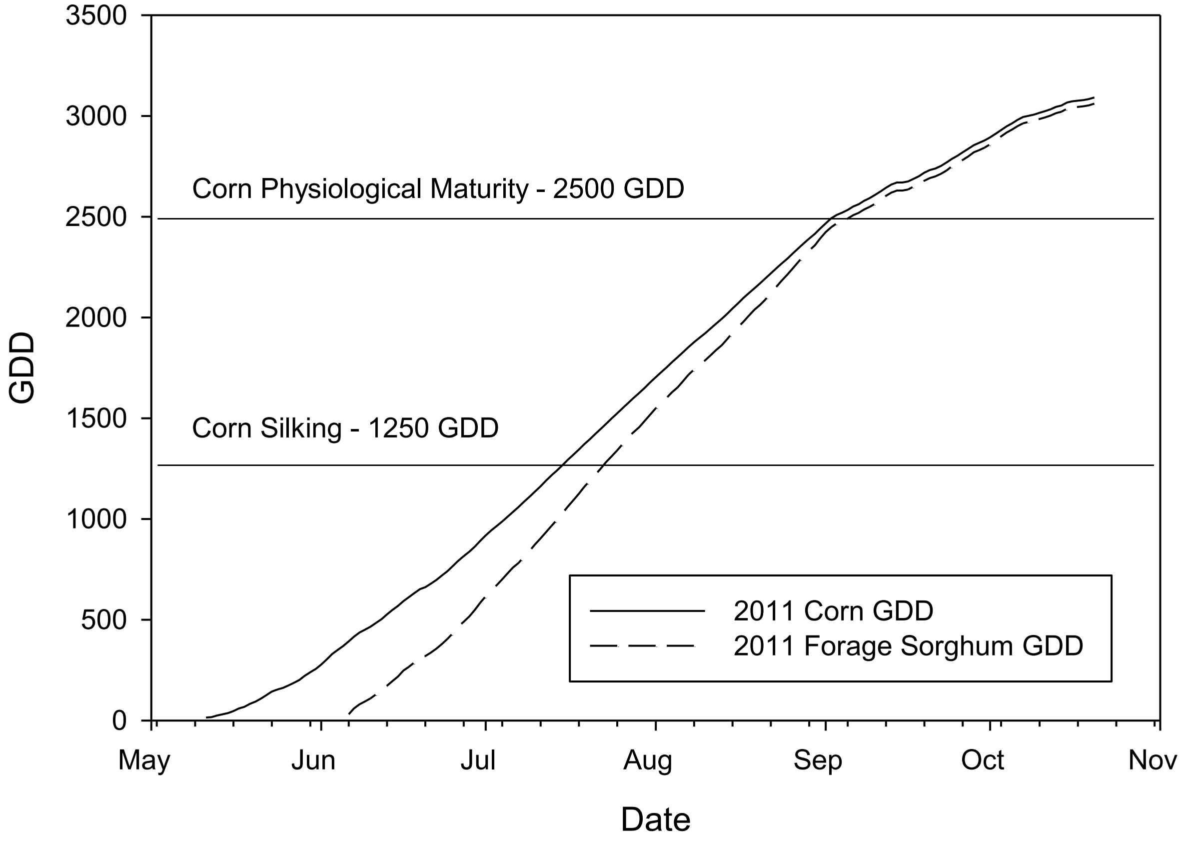


Figure 2-2. Cumulative growing degree days (GDD) for corn and forage sorghum, Tribune, Kansas 2011.

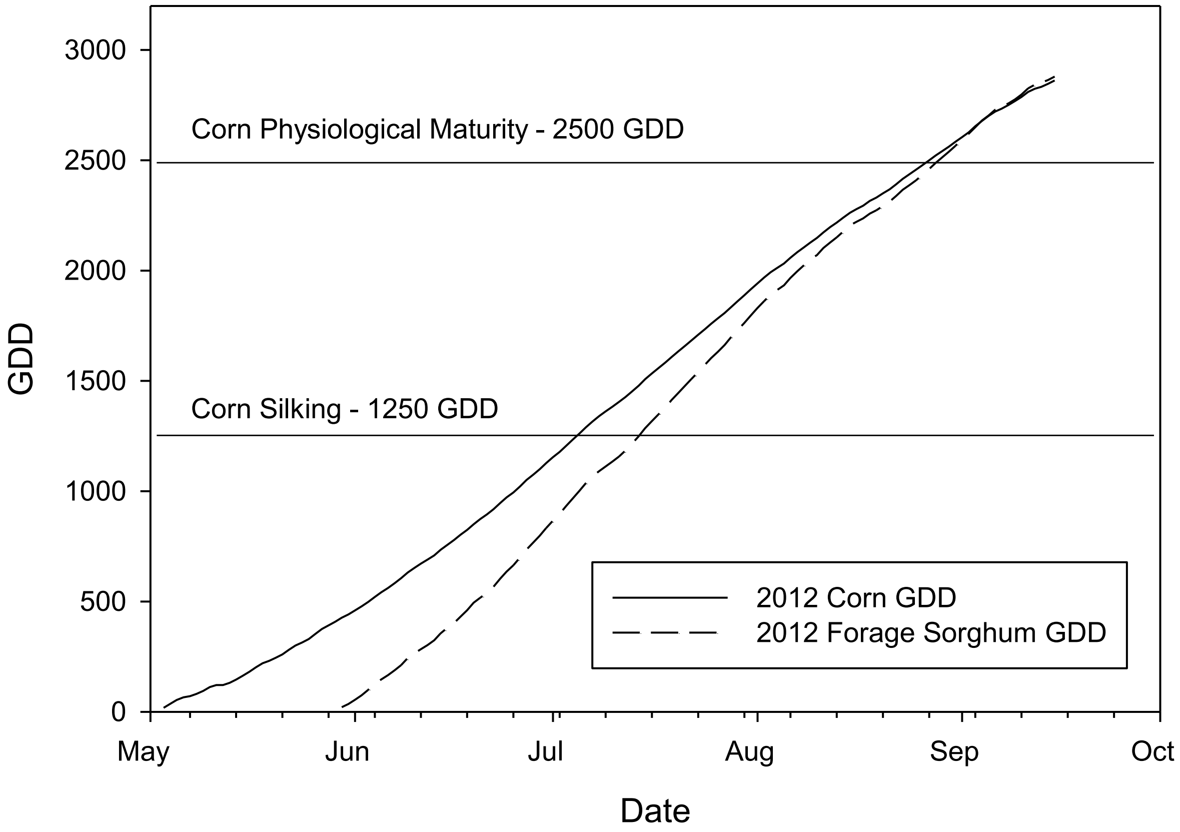


Figure 2-3. Cumulative growing degree days (GDD) for corn and forage sorghum, Tribune, Kansas 2012.

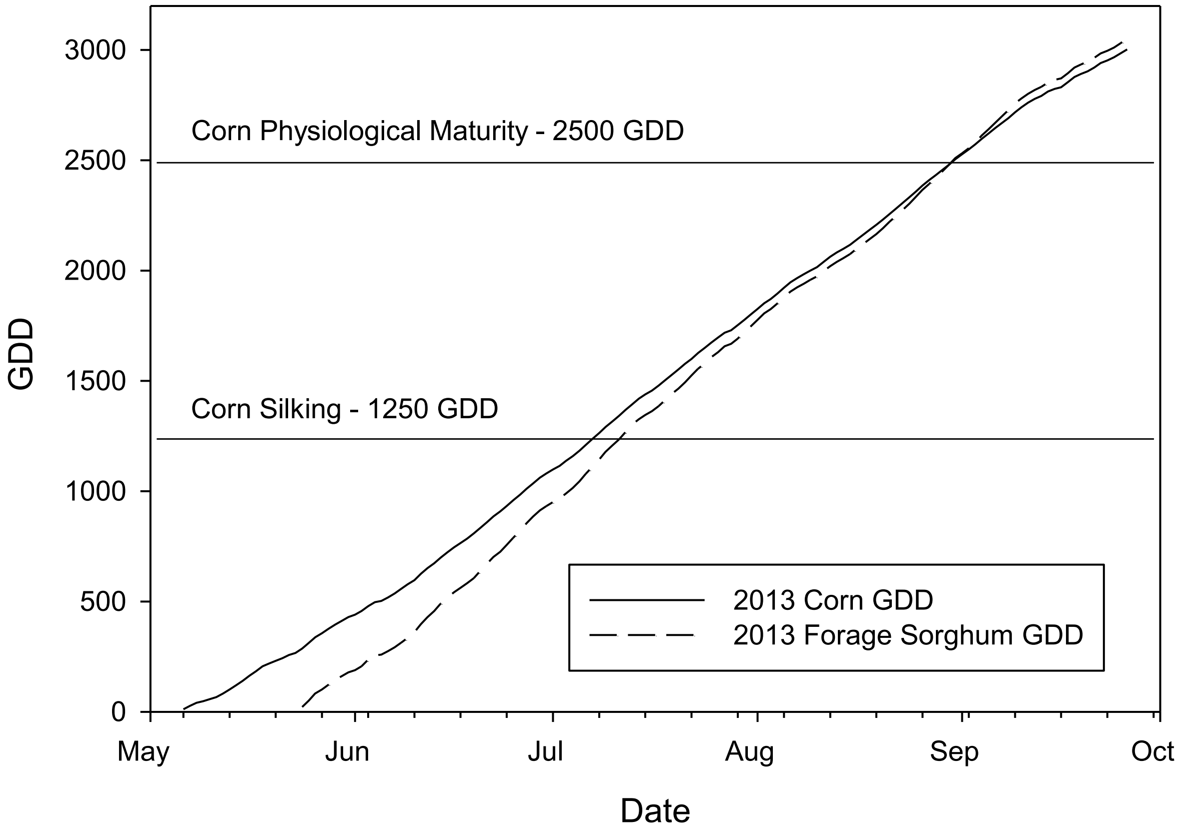


Figure 2-4. Cumulative growing degree days (GDD) for corn and forage sorghum, Tribune, Kansas 2013.

Table 2-3. Irrigation amounts by month for Tribune, Kansas 2011, 2012 and 2013.

	2011	2012	2013
		mm	
Apr	72.9	-	38.1
May	20.3	20.1	80.0
Jun	110.9	96.5	140.9
Jul	186.6	156.2	36.8
Aug	151.1	249.9	40.6
Sep	68.5	-	38.8
Total	610.3	522.7	375.2

Table 2-4 Irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn biomass, irrigated and dryland treatments analyzed separately, Tribune, Kansas 2011, 2012 and 2013.

Year	P>F	Irrigated forage sorghum		Irrigated corn		P>F	Dryland forage sorghum		Dryland corn	
					Mg ha^{-1}					
2011	0.170	21.1		16.0		0.981	11.1		11.0	
2012	0.002	20.8	a	9.8	b	0.028	6.1	a	3.9	b
2013	0.195	20.6		17.6		0.167	16.1		11.6	

†Letters within an irrigated or dryland group treatment represent differences at LSD (0.05)

Table 2-5. Corn grain yield and corn harvest index, Tribune, Kansas 2011, 2012 and 2013.

Year	Irrigated Corn Grain Yield	SE	Dryland Corn Grain Yield	SE	Irrigated Corn Harvest Index	SE	Dryland Corn Harvest Index	SE
	kg ha^{-1}		kg ha^{-1}					
2011	8868	1876	6776	599	0.57	0.021	0.59	0.004
2012	7358	168	2667	125	0.63	0.010	0.58	0.013
2013	12425	313	7391	455	0.60	0.024	0.59	0.024

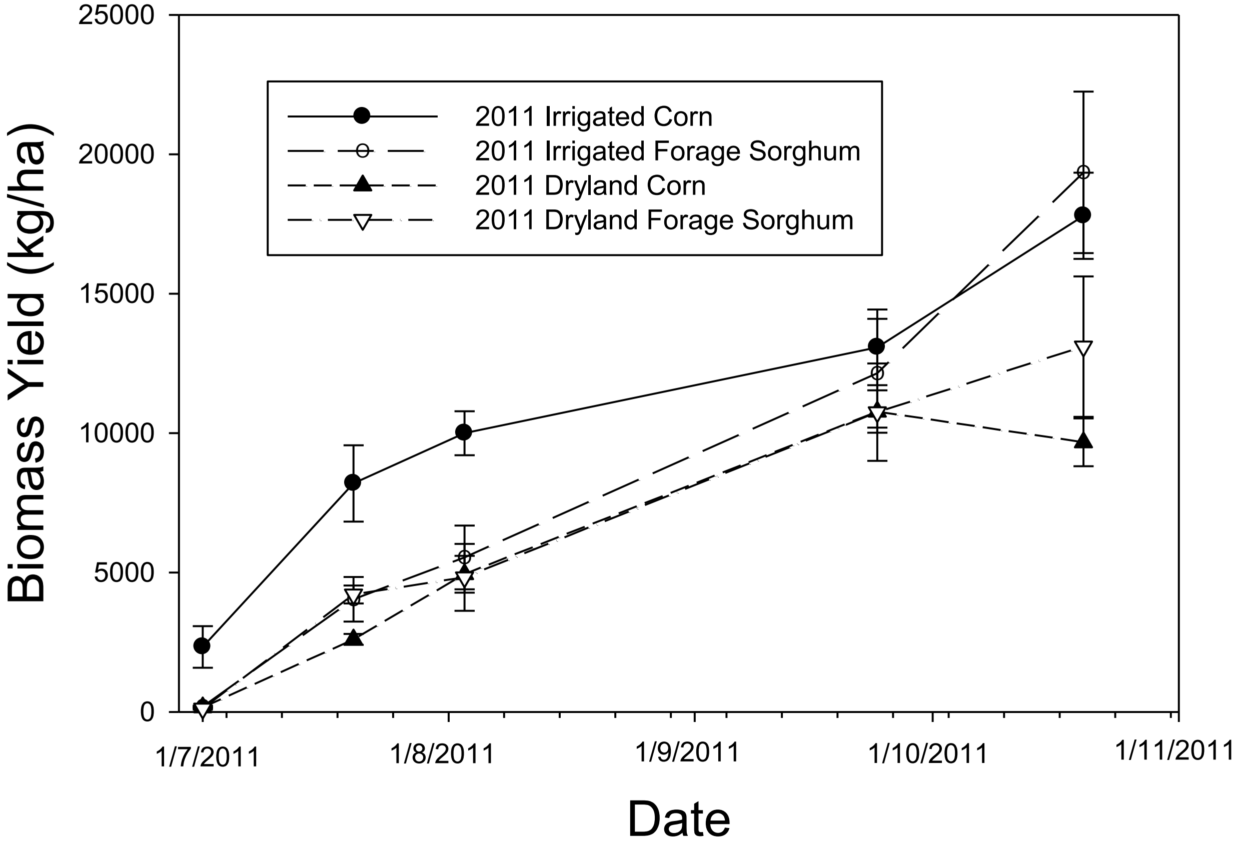


Figure 2-5. Biomass accumulation for season, Tribune, Kansas 2011.

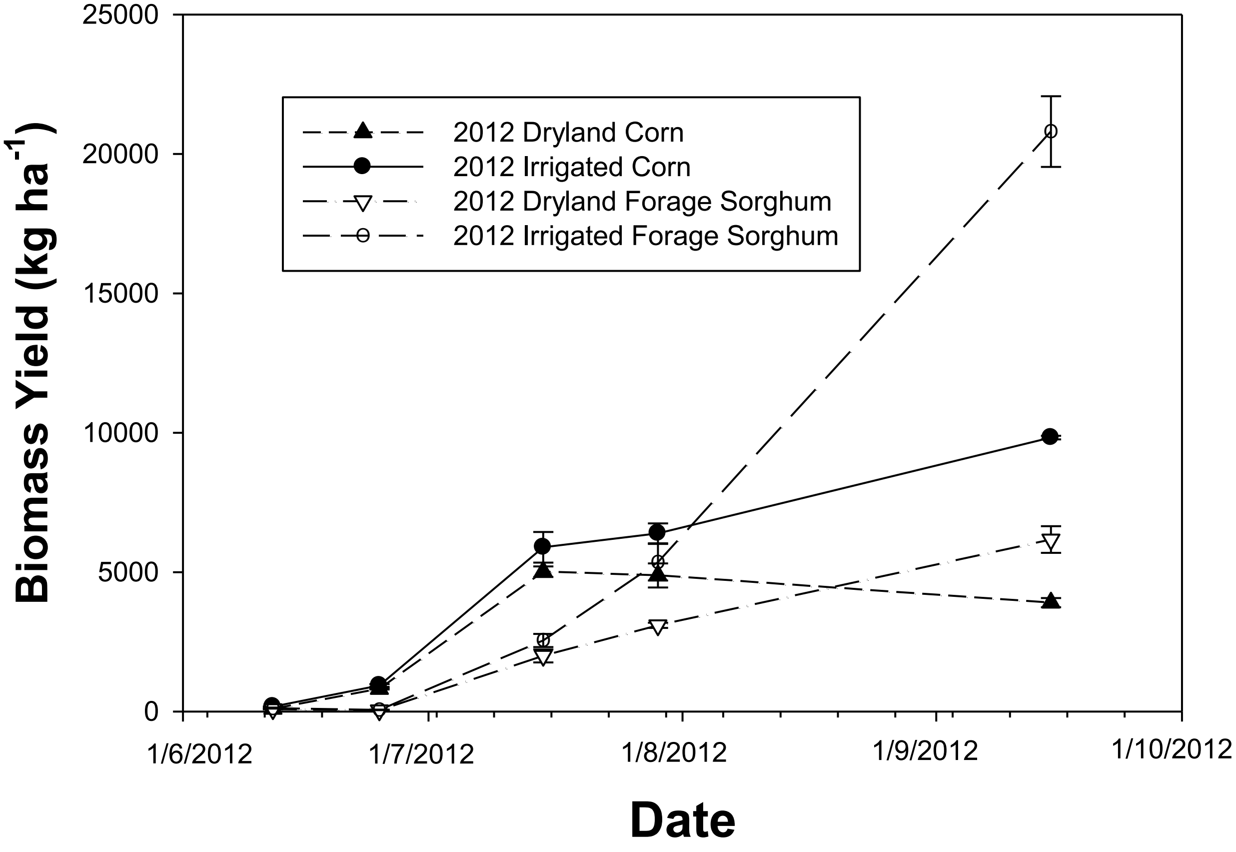


Figure 2-6. Biomass accumulation for season, Tribune, Kansas 2012.

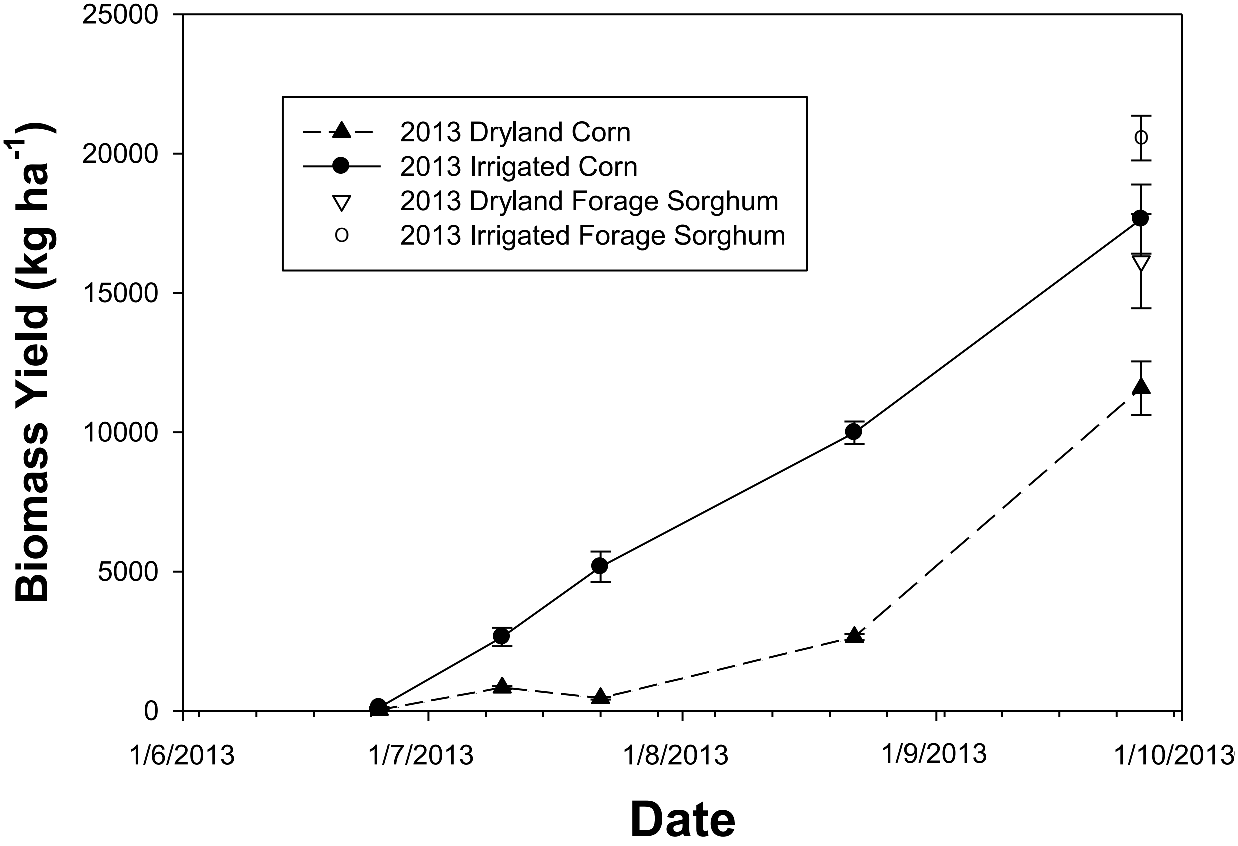


Figure 2-7. Biomass accumulation for season, Tribune, Kansas 2013.

Table 2-6 Available soil water by depth for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn, irrigated treatments analyzed separately from dryland treatments, Tribune, Kansas 2011.

Date	Depth	P>F	Irrigated forage sorghum		Irrigated Corn		P>F	Dryland forage sorghum	Dryland corn
	cm				Available water content, cm^3 cm^{-34}				
1/7/2011	30	0.008	0.150	a	0.127	b	0.952	0.165	0.164
	61	0.014	0.125	a	0.103	b	0.240	0.162	0.152
	91	0.536	0.123		0.116		0.496	0.161	0.164
	122	0.604	0.124		0.115		0.829	0.167	0.167
	152	0.463	0.111		0.104		0.988	0.166	0.165
	183	0.595	0.102		0.092		0.473	0.162	0.163
20/7/2011	30	0.069	0.123		0.095		0.248	0.086	0.090
	61	0.007	0.115	a	0.041	b	0.214	0.104	0.134
	91	0.013	0.110	a	0.050	b	0.577	0.147	0.150
	122	0.051	0.122		0.088		0.950	0.172	0.171
	152	0.078	0.129		0.096		0.818	0.175	0.160
	183	0.195	0.116		0.109		0.903	0.178	0.173
3/8/2011	30	0.149	0.129		0.188		0.352	0.200	0.183
	61	0.151	0.151		0.115		0.626	0.131	0.126
	91	0.113	0.136		0.074		0.566	0.127	0.135
	122	0.101	0.155		0.087		0.760	0.153	0.152
	152	0.031	0.145	a	0.089	b	0.715	0.165	0.154
	183	0.026	0.134	a	0.093	b	0.879	0.168	0.164
23/8/2011	30	0.059	0.144		0.153		0.875	0.161	0.115
	61	0.165	0.130		0.118		0.226	0.112	0.092
	91	0.115	0.131		0.094		0.901	0.128	0.114
	122	0.135	0.138		0.082		0.915	0.142	0.136
	152	0.077	0.149		0.096		0.825	0.154	0.158
	183	0.019	0.136	a	0.091	b	0.712	0.156	0.169
20/10/2011	30	0.022	0.143	b	0.160	a	0.165	0.164	0.185
	61	0.301	0.105		0.104		0.833	0.101	0.102
	91	0.621	0.092		0.081		0.943	0.095	0.085
	122	0.983	0.098		0.092		0.900	0.114	0.114
	152	0.658	0.097		0.099		0.823	0.122	0.127
	183	0.890	0.095		0.098		0.334	0.131	0.144

†Letters within an irrigated or dryland treatment group represent differences at LSD (0.05)

Table 2-7 Available soil water by depth for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn, irrigated treatments analyzed separately from dryland treatments, Tribune, Kansas 2012.

Date	Depth	P>F	Irrigated forage sorghum		Irrigated Corn		P>F	Dryland forage sorghum		Dryland corn	
	cm				Available water content, $cm^3\ cm^{-3}$						
12/6/2012	30	0.368	0.171		0.172		0.735	0.173		0.173	
	61	0.187	0.134		0.158		0.966	0.148		0.142	
	91	0.039	0.147		0.169		0.515	0.132		0.122	
	122	0.155	0.134		0.157		0.963	0.135		0.125	
	152	0.687	0.135		0.132		0.466	0.124		0.122	
	183	0.974	0.122		0.121		0.570	0.116		0.127	
25/6/2012	30	0.004	0.186	a	0.172	b	0.281	0.175		0.155	
	61	0.455	0.145		0.147		0.838	0.135		0.135	
	91	0.872	0.153		0.155		0.371	0.136		0.136	
	122	0.679	0.163		0.156		0.293	0.147		0.130	
	152	0.550	0.149		0.148		0.376	0.140		0.137	
	183	0.949	0.132		0.134		0.211	0.131		0.126	
25/7/2012	30	0.235	0.107		0.085		0.222	0.092		0.086	
	61	0.448	0.119		0.098		0.468	0.111		0.093	
	91	0.371	0.155		0.139		0.271	0.136		0.115	
	122	0.702	0.153		0.144		0.029	0.149	a	0.123	b
	152	0.203	0.156		0.131		0.115	0.142		0.136	
	183	0.526	0.146		0.132		0.180	0.144		0.129	
29/7/2012	30	0.816	0.080		0.085		0.444	0.082		0.062	
	61	0.981	0.076		0.074		0.809	0.061		0.054	
	91	0.537	0.103		0.070		0.580	0.063		0.045	
	122	0.392	0.111		0.088		0.376	0.087		0.068	
	152	0.640	0.121		0.113		0.121	0.118		0.092	
	183	0.787	0.124		0.116		0.125	0.127		0.105	
15/9/2012	30	0.865	0.065		0.069		0.957	0.064		0.066	
	61	0.531	0.052		0.068		0.945	0.065		0.063	
	91	0.858	0.055		0.054		0.909	0.037		0.034	
	122	0.749	0.044		0.064		0.900	0.026		0.020	
	152	0.889	0.051		0.052		0.963	0.023		0.024	
	183	0.771	0.073		0.065		0.961	0.042		0.041	

†Letters within an irrigated or dryland treatment group represent differences at LSD (0.05)

Table 2-8. Available soil water by depth for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn, irrigated treatments analyzed separately from dryland treatments, Tribune, Kansas 2013.

Date	Depth	P>F	Irrigated forage sorghum		Irrigated Corn		P>F	Dryland forage sorghum		Dryland corn	
	cm				Available water content, cm^3 cm^{-3}						
25/6/2013	30	0.613	0.172		0.173		0.744	0.162		0.162	
	61	0.845	0.054		0.062		0.701	0.067		0.064	
	91	0.549	0.162		0.154		0.058	0.122		0.144	
	122	0.716	0.135		0.143		0.812	0.124		0.125	
	152	0.142	0.089		0.110		0.284	0.095		0.110	
	183	0.300	0.062		0.085		0.488	0.060		0.081	
10/7/2013	30	0.072	0.174	a	0.156	b	0.749	0.166		0.151	
	61	0.066	0.165		0.141		0.675	0.142		0.139	
	91	0.278	0.162		0.150		0.847	0.132		0.125	
	122	0.635	0.131		0.132		0.725	0.125		0.115	
	152	0.524	0.106		0.114		0.780	0.102		0.104	
	183	0.217	0.076		0.105		0.694	0.094		0.087	
22/7/2013	30	0.855	0.155		0.157		0.864	0.157		0.151	
	61	0.129	0.159		0.138		0.327	0.142		0.130	
	91	0.156	0.160		0.155		0.358	0.135		0.122	
	122	0.207	0.142		0.121		0.187	0.126		0.111	
	152	0.924	0.111		0.114		0.347	0.114		0.104	
	183	0.855	0.105		0.101		0.178	0.109		0.093	
22/8/2013	30	0.009	0.137	b	0.160	a	0.089	0.142		0.163	
	61	0.302	0.151		0.144		0.990	0.131		0.131	
	91	0.205	0.160		0.153		0.437	0.135		0.124	
	122	0.282	0.143		0.132		0.043	0.144	a	0.102	b
	152	0.950	0.132		0.126		0.067	0.135		0.115	
	183	0.996	0.121		0.125		0.262	0.136		0.118	
26/9/2013	30	0.001	0.124	b	0.162	a	0.002	0.112	b	0.178	a
	61	0.007	0.112	b	0.140	a	0.092	0.107		0.137	
	91	0.653	0.112		0.128		0.483	0.088		0.094	
	122	0.813	0.108		0.092		0.865	0.089		0.083	
	152	0.885	0.092		0.090		0.299	0.095		0.079	
	183	0.922	0.103		0.101		0.483	0.092		0.089	

†Letters within an irrigated or dryland treatment group represent differences at LSD (0.05)

Table 2-9. Available soil water for the 183 cm profile, irrigated and dryland treatments analyzed separately, Tribune, Kansas 2011.

	1/7/2011	20/7/2011	3/8/2011	23/8/2011	20/10/2011
	Available soil water mm in 183 cm soil profile				
Irrigated forage sorghum	227	219 a	278 a	253	192
Irrigated corn	205	144 b	197 b	196	199
Dryland forage sorghum	299	259	288	244	223
Dryland corn	302	274	285	239	234

†Letters within an irrigated or dryland treatment group represent differences at LSD (0.05)

Table 2-10. Available soil water for the 183 cm profile, irrigated and dryland treatments analyzed separately, Tribune, Kansas 2012.

	12/6/2012	25/6/2012	15/7/2012	29/7/2012	15/9/2012
	Available soil water mm in 183 cm soil profile				
Irrigated forage sorghum	262	283	249	189	103
Irrigated corn	277	279	224	165	111
Dryland forage sorghum	253	265	235	166	76
Dryland corn	251	252	205	133	80

†Letters within an irrigated or dryland treatment group represent differences at LSD (0.05)

Table 2-11. Available soil water for the 183 cm profile, irrigated and dryland treatments analyzed separately, Tribune, Kansas 2013.

	25/6/2013	10/7/2013	22/7/2013	22/8/2013	26/9/2013
	Available soil water mm in 183 cm soil profile				
Irrigated forage sorghum	236	251	259	262	198
Irrigated corn	254	244	241	259	222
Dryland forage sorghum	220	231	236	252	178
Dryland corn	237	223	217	233	196

†Letters within an irrigated or dryland treatment group represent differences at LSD (0.05)

Table 2-12. Total end of season water use for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn, irrigated treatments analyzed separately from dryland treatments, Tribune, Kansas 2011, 2012 and 2013.

Year	P>F	Irrigated forage sorghum		Irrigated corn		P>F	Dryland forage sorghum	Dryland corn
Total water use, mm								
2011	0.008	773	a	744	b	0.831	408	400
2012	0.545	663		659		0.497	284	291
2013	0.023	544	b	581	a	0.073	387	342

†Letters within an irrigated or dryland treatment group represent differences at LSD (0.05)

Table 2-13. Water use efficiency (WUE_b) for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn, irrigated treatments analyzed separately from dryland treatments, Tribune, Kansas 2011, 2012 and 2013.

Year	P>F	Irrigated forage sorghum		Irrigated corn		P>F	Dryland forage sorghum		Dryland corn	
					kg ha^{-1} mm^{-1}					
2011	0.225	27.1		21.5		0.923	27.0		27.9	
2012	0.003	31.3	a	14.9	b	0.040	21.8	a	13.4	b
2013	0.092	37.7		30.3		0.428	41.7		34.3	

†Letters within an irrigated or dryland treatment group represent differences at LSD (0.05)

Table 2-14. Water use efficiency (WUE_g) for corn grain, Tribune, Kansas.

Year	Irrigated corn WUEg	SE	Dryland corn WUEg	SE
	kg ha^{-1} mm^{-1}		kg ha^{-1} mm^{-1}	
2011	10.21	2.3456	14.90	0.6852
2012	9.44	0.3010	7.76	0.4823
2013	18.05	0.5230	20.01	1.7180

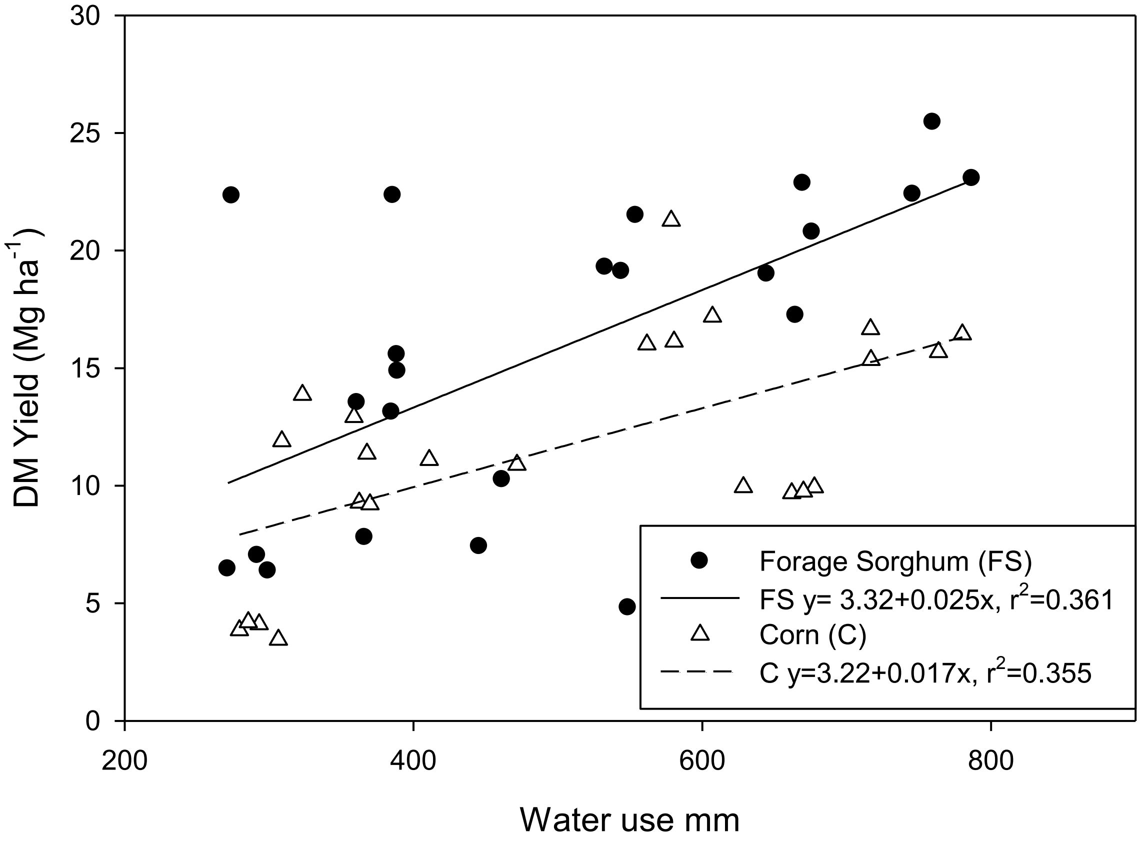


Figure 2-8. Dry matter (DM) biomass yield vs water use for Tribune, Kansas 2011, 2012 and 2013.

Table 2-15 Fraction of intercepted photosynthetically active radiation (IPAR) for irrigated corn, irrigated sorghum, dryland corn and dryland sorghum, irrigated treatments analyzed separately from dryland treatments, Tribune, Kansas 2011.

Date	P>F	Irrigated forage sorghum		Irrigated corn		P>F	Dryland forage sorghum		Dryland corn	
					Fraction of PAR intercepted (Θ)					
1/7/2011	0.004	0.058	b	0.553	a	0.443	0.023		0.017	
20/7/2011	0.042	0.713	b	0.860	a	0.172	0.502		0.353	
3/8/2011	0.454	0.722		0.887		0.077	0.901		0.596	
23/8/2011	<0.0001	0.989	a	0.711	b	<0.0001	0.989	a	0.630	b
20/10/2011	<0.0001	0.928	b	0.447	a	<0.0001	0.911	a	0.459	b

†Letters within a row represent differences at LSD (0.05)

Table 2-16. Fraction of intercepted photosynthetically active radiation (IPAR) for irrigated corn, irrigated sorghum, dryland corn and dryland sorghum, irrigated treatments analyzed separately from dryland treatments, Tribune, Kansas 2012.

Date	P>F	Irrigated forage sorghum		Irrigated corn		P>F	Dryland forage sorghum		Dryland corn	
					Fraction of PAR intercepted					
12/6/2012	<0.0001	0.018	b	0.019	a	0.0002	0.014	b	0.298	a
25/6/2012	0.0003	0.052	b	0.306	a	0.360	0.105		0.240	
15/7/2012	0.148	0.819		0.879		0.871	0.552		0.559	
29/7/2012	0.004	0.991	a	0.961	b	0.935	0.686		0.692	
15/9/2012	<0.0001	0.920	a	0.532	b	0.001	0.884	a	0.312	b

†Letters within a row represent differences at LSD (0.05)

Table 2-17. Fraction of intercepted photosynthetically active radiation (IPAR) for irrigated corn, irrigated sorghum, dryland corn and dryland sorghum, irrigated treatments analyzed separately from dryland treatments, Tribune, Kansas 2013.

Date	P>F	Irrigated forage sorghum		Irrigated corn		P>F	Dryland forage sorghum		Dryland corn	
					Fraction of PAR intercepted					
25/6/2013	0.003	0.016	b	0.031	a	0.019	0.016	b	0.059	a
10/7/2013	0.012	0.486	b	0.838	a	0.007	0.187	b	0.297	a
22/7/2013	0.053	0.838		0.911		0.379	0.726		0.634	
22/8/2013	0.014	0.991	a	0.812	b	<0.0001	0.960	a	0.684	b
26/9/2013	0.003	0.986	a	0.819	b	<0.0001	0.983	a	0.810	b

†Letters within a row represent differences at LSD (0.05)

Table 2-18. Fraction of crude protein for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn. Forage sorghum analyzed separately from corn. Tribune, Kansas 2012 and 2013.

Year	P>F	Irrigated forage sorghum		Dryland forage sorghum		P>F	Irrigated corn	Dryland corn
				Fraction of Crude Protein				
2012	0.0153	7.48	a	9.92	b	1.000	6.47	6.47
2013	0.0544	6.40		7.34		0.405	6.30	6.6

†Letters within a crop treatment group represent differences at LSD (0.05)

Table 2-19. Fraction of acid detergent fiber (ADF) for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn. Forage sorghum analyzed separately from corn Tribune, Kansas 2012 and 2013.

Year	P>F	Irrigated forage sorghum		Dryland forage sorghum		P>F	Irrigated corn		Dryland corn	
					Fraction of ADF					
2012	.0005	40.15	a	27.11	b	0.957	34.425		34.52	
2013	0.319	45.10		42.8		0.015	43.65	a	38.25	b

†Letters within a crop treatment group represent differences at LSD (0.05)

Table 2-20. Fraction of neutral detergent fiber (NDF) for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn. Forage sorghum analyzed separately from corn Tribune, Kansas 2012 and 2013.

Year	P>F	Irrigated forage sorghum		Dryland forage sorghum		P>F	Irrigated corn		Dryland corn	
					Fraction of NDF					
2012	0.001	62.75	a	54.19	b	0.448	57.86		60.13	
2013	0.304	65.80		64.05		0.029	65.13	a	58.60	b

†Letters within a crop treatment group represent differences at LSD (0.05)

Table 2-21. Nitrates for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn. Forage sorghum analyzed separately from corn Tribune, Kansas 2012 and 2013.

Year	P>F	Irrigated forage sorghum	Dryland forage sorghum	P>F	Irrigated corn		Dryland corn	
			Nitrate mg kg^{-1} NO_3-N					
2012	0.161	1342.50	955.75	0.01	662.50	a	1812.50	b
2013	0.172	1034.75	882.75	0.56	716.25		556.75	

†Letters within an crop treatment group represent differences at LSD (0.05)

Table 2-22. Prussic acid for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn. Forage sorghum analyzed separately from corn Tribune, Kansas 2012 and 2013.

Year	P>F	Irrigated forage sorghum		Dryland forage sorghum			P>F	Irrigated corn	Dryland corn
						mg/kg			
2012	0.003	146.50	a	690.05	b		0.19	51.75	32.00
2013	0.241	145.75		121.50			0.65	33.50	35.5

†Letters within an crop treatment group represent differences at LSD (0.05)

References

Al-Kasi, M.M., A.F. Berrada, and M.W. Stack. 1997. Evaluation of irrigation scheduling program and spring wheat yield response in southwestern Colorado. Agric. Water Manage. 34:137-148.

Ankom. 2006. Ankom Technology Method 5. Acid detergent fiber in feeds. Filter Bag Technique. Ankom Technology. Macedon, New York. Modification of method AOAC Official Method 973.18. Fiber (acid detergent) and Lignin (H_2SO_4) in animal feed. Official methods analysis of AOAC International. 19th ed. Dr. George Latimer, Jr (ed). Gaithersburg, Maryland.

Ankom 2006. Ankom Technology Method 6. Neutral detergent fiber in feeds. Filter Bag Technique. Ankom Technology. Macedon, New York. Modification of method AOAC Official Method 2002.04. Amylase-treated neutral detergent fiber in feeds. Using refluxing in beakers or crucibles. Official Methods of Analysis of AOAC International. 19th ed. Dr. George W. Latimer, Jr (ed). Gaithersburg Mayrland.

AOAC International. 2012. AOAC Official Method 990.03. Protein (crude) in animal feed. Combustion method. Official Methods of Analysis of AOAC International. 19th ed. Dr. George W. Latimer, Jr (ed). Gaithersburg, Maryland.

Arkin, G.F., W. D. Rosenthal, and W. R. Jordan. 1983. A sorghum leaf area model. ASAE Tech Paper 83-2098. Am. Soc. Agric. Eng., St. Joseph, Mich.

Aydin, G., R.J. Grant, and J. O’Rear. 1999. Brown midrib sorghum in diets for lactating dairy cows. J. Dairy Sci. 82:2127-2135.

Bean, B.W., R. L. Baumhardt, F. T. McCollum III, and K.C. McCuistion. 2013. Comparison of sorghum classes for grain and forage yield and forage nutritive value. Field Crops Res. 142:20-26.

Boote, K.J., and R.S. Loomis. 1991. The prediction of canopy photosynthesis. In: Boote, K.J., R.S. Loomis (Eds.), Modeling Photosynthesis-From Biochemistry to Canopy. CSSA Special Publication Number 19. Crop Science Society of America, Inc./American Society of Agronomy, Inc, Madison, Wisconsin, pp.109-140.

Cataldo, D.A., M. Haroon, L.E. Schrader, and V.L. Young, 1975. Rapid colorimetric determination of nitrate in plant tissue by nitration of salicylic acid. Comm. Soil. Sci. and Plant Ana. 6:71-80.

Condon, A.G., R.A. Richards., and G.J. Rebetzke, G.D. Farquhar. 2004. Breeding for high water use efficiency. J. Exp. Bot. 55:2447-2460.

Cox, W.J. J.H. Cherney, D.J.R. Cherney, and W.D. Pardee. 1994. Forage quality and harvest index of corn hybrids under different growing conditions. Agron. J. 86:277-282.

Cummings, D.G. 1981. Yield and quality changes with maturity of silage-type sorghum fodder. Agron. J. 73:988-990.

Dahlberg, J. 2000. Classification and characterization of sorghum. In: Smith, C.W., Frederiksen, R.A. (Eds.), Sorghum: Origin, History, Technology, and Production. John Wiley & Sons, Inc., New York, NY, pp. 99-130.

Denmead, O.T. and R.H. Shaw. 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron J. 52:272-274.

Dennehy, K.F. 2000. High Plains regional ground water study USGS Fact Sheet FS-091-00. U.S. Geol. Survey, Lincoln, NE.

Egekeze, J.O. and F. W. Oehme. 1980. Cyanides and their toxicity: A literature review. The Vetern. Quart. 2:104-114

Evans, L.T. 1993. Crop Evolution, Adaptation and Yield. Cambridge University Press, Cambridge, UK.

Frank, B.J., A.J. Schlegel, L.R. Stone and M.B. Kirkham. 2013. Grain Yield and Plant Characteristics of Corn Hybrids in the Great Plains.

Gillingham, J.T. M.M. Shirer, and N.R. Page. 1969. Evaluation of the Orion Cyanide Electrode for estimating the cyanide content of forage samples. Agron. J. 61:717-718.

Hao, B., Q. Xue, B.W. Bean, W.L. Rooney, and J.D. Becker. 2014. Biomass production, water and nitrogen use efficiency in photoperiod-sensitive sorghum in the Texas High Plains. Biomass Bioenerg. 62:108-116.

Hao, B., Q. Xue, B.W. Bean, W.L. Rooney, and J.D. Becker. 2014. Biomass production, water and nitrogen use efficiency in photoperiod-sensitive sorghum in the Texas High Plains. Biomass and Bioener. 62:108-116.

Harms, C.L. and B. B. Tucker. (1973). Influence of nitrogen fertilization and other factors on yield, prussic acid, nitrate and total nitrogen concentrations of sudangrass cultivars. Agron. J. 65:22-26.

Hattendorf, M. J., M. S. Redelfs, B. Amos, L.R. Stone and R. E. Gwin Jr. 1998. Comparitive water use characteristics of six row crops. Agron. J. 80:80-85.

Howell, T., A. Yazar, A. D. Schneider and D. A. Dusek. 1995. Yield and water use efficiency of corn in response to LEPA irrigation. Trans. ASAE 38:1737-1747.

Howell, T.A., J.L. Steiner, A.D. Schneider, S.R. Evett, and J.A. Tolk. 1997. Seasonal and maximum daily evapotranspiration of irrigated wheat, sorghum, and corn- Southern High Plains. Trans. Am. Soc. Agric. Eng. 40:623-634.

Howell, T.A., S.R. Evett, J.A. Tolk, K.S. Copeland, and P.D. Colaizzi, P.H. Gowda. 2008. Evapotranspiration of corn and forage sorghum for silage. In: Soil and water Management Research News. USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, USA. Wetting Front Newsletter 10 (June (1)).

Johnson, R.R., and K.E. McClure. 1968. Corn plant maturity: IV. Effects on digestibility of corn silage in sheep. J. Anim. Sci. 27:535-539.

Klocke, N.L., L.R. Stone, G. A. Clark, T.J. Dumler, and S. Briggeman. 2006. Water allocation model for limited irrigation Applied Eng. in Agric. (22)3:381-389.

KWO. 2011. 2011 Kansas water use reporting. Topeka, Kans.: Kansas Water Office.

Lamm, F.R., L.R. Stone and D.M. O'Brien. 2007. Crop production and economics in Northwest Kansas as related to irrigation capacity. 23(6):737-745.

Lauer, J.G., J.G. Coors, and P.J. Flannery. 2001. Forage yield and quality of corn cultivars developed in different eras. Crop Sci. 41:1449-1455.

Marsalis, M.A., and B. Bean. 2010. Western forage production guide. Lubbock, TX, USA: United Sorghum Checkoff Program, Available from http://amarillo.tamu.edu/files/2010/11/WesternForageGuide_FINAL.pdf

Marsalis, M.A., S.V. Angadi, and F.E. Contreras-Govea. 2010. Dry matter yield and nutritive value of corn, forage sorghum, and BMR forage sorghum at different plant populations and nitrogen rates. Field Crops Res. 116:52-57.

Martin, D. L., J. R. Gilley, and R. J. Supalla. 1989. Evaluation of irrigation planting decisions. Journal of Irrigation and Drainage Engineering. 115:58-77.

McCollum, T., K. McCuistion, and B. Bean. 2005. Brown midrib and photoperiod-sensitive forage sorghum. In: Proceedings of the 2005 plains nutrition council spring conference; Apr 14-15; San Antonio, TX. Amarillo, TX, USA; Texas A&M Univ. Ag. Res. and Ext. Center; pp. 36-46.

McCuistion, K.C., B.W. Bean, and F.T. McCollum III. 2009. Yield and water-use efficiency response to irrigation level of brown midrib, non-brown midrib and photoperiod-sensitive forage sorghum cultivars. Forage and Grazinglands. 10.1094/FG-2009-0909-01-RS.

McCuistion, K.C., B.W. Bean, F.T. McCollum III. 2010. Nutritional composition response to yield differences in brown midrib, non-brown midrib, and photoperiod sensitive forage sorghum cultivars. Forage and Grazinglands doi:10.1094/FG-2010-0428-01-RS.

McGuire, V.L. 2004. Water-level changes in the High Plains Aquifer, predevelopment to 2002, 1980 to 2002, and 2001 to 2002. USGS Fact Sheet FS-2004-3026. U.S. Geological Survey, Denver, CO.

McMaster, G.S. and W.W. Wilhelm. 1997. Growing degree-days: one equation, two interpretations. Agric. Forest Meteorol.. 87:291-300.

Miron, J., E. Zuckerman, G. Adin, R. Soloman, E. Shoshani, M. Nikbachat, E. Yosef, A. Zenou, Z. Gershon Weinberg, Y. Chen, I. Halachmi, and D. Ben-Ghedalia. 2007. Comparison of two forage sorghum varieties with corn and the effect of feeding their silages on eating behavior and lactation performance of dairy cows. Anim. Feed Sci. Technol. 139:23-29.

Muchow, R.C., T.R. Sinclair, and J.M. Bennett. 1990. Temperature and solar radiation effects on potential maize yield across locations. Agron. J. 82:338-343.

Norwood, C. A. 2000. Water use and yield of limited-irrigated and dryland corn. Soil Sci. Soc. Am. J. 64:365-370.

NRC (National Research Council), 2001. Nutrient Requirements of Dairy Cattle: Seventh Revised Edition. National Academies Press, Washington, D.C.

Olson, T. 1971. Yield and water use by different populations of dryland corn, grains sorghum, and forage sorghum in the Western corn belt. Agron. J. 63:104-406.

Pioneer Hi-bred International Inc. 35F48 Corn Seed. Pioneer, Johnson, IA. https://www.pioneer.com/home/site/us/

Rooney, W. L., J. Blumenthal, B. Bean, and J.E. Mullet. 2007. Designing sorghum as a dedicated bioenergy feedstock. Biofuels Bioprod. Bioref. 2:147-157.

Rosenthal, W.D., G.F. Arkin, P. J. Shouse, and W. R. Jordan. 1987. Water deficit effects on transpiration and leaf growth. Agron J. 79:1019-1026.

Sanchez, A. C., P.K. Subudhi, D.T Rosenow, and H.T. Nguyen. 2002. Mapping QTLs associated with drought resistance in sorghum (*Sorghum bicolor* L. Moench). J. Plant Mol. Biol. 48:713-726.

Schlegel, A. J., and J.L. Havlin. 1995. Corn response to long-term nitrogen and phosphorus fertilization. J. Prod. Agric. 8:181-185.

Sinclair, T.R., C.B. Tanner, and J.M. Bennett. 1984. Water-use efficiency in crop production. BioScience. 34:36-40.

Sorghum Partners Inc., 2015. 1990 Hybrid Forage Sorghum, Technical Information. Sorghum Partners Inc. New Deal, TX, Available at http://www.chromatininc.com/products/25/1990

Steward, D. R., P. J. Bruss, X. Yang, S. A. Staggenborg, S. M.Welch, and M. D. Apley. 2013. Proc. Natl. Acad. Sci. USA. 110:3477-3486.

Stone, L.R., A. J. Schlegel, A. H. Khan, N. L. Klocke, and R. M. Aiken. 2006. Water Supply: Yield relationships developed for study of water management. J. Nat. Resour. Life. Sci. Educ. 35:161-173.

Stone, L.R., N.L. Klocke, A.J. Schlegel, F.R. Lamm and D.J. Tomsicek. 2011. Equations for drainage component of the field water balance. App. Eng. Aric. 27:345-350.

Tolk, J. A., and T. A. Howell. 2003. Water use efficiencies of grain sorghum grown in three USA southern Great Plains soils. Agric. Water Manage. 59:97-111.

Turner, N.C. 1974. Stomatal behavior and water status of maize, sorghum and tobacco under field conditions. II. At low soil water potential. Plant Physiol. 55:360-365.

Weichenthal, B. A., Baltensperger, D.D., Vogel, K. P., Masterson, S. D., Blumenthal, J. M., and Krall, J. M. 2003. Annual forages for the Nebraska Panhandle. Tech. Bull. No. G1527. Univ. of Nebraska, Lincoln, NE.

Wheeler, J.L., C. Mulchay, J.J. Walcott and G.G. Rapp. 1990. Factors affecting the hydrogen cyanide potential of forage sorghum. Austral. J. Agric. Res. 41:1093-1100.

Yimam, Y.T., T. E. Ochsner, and V. G. Kakani. 2015. Evapotranspiration partitioning and water use efficiency of switchgrass and biomass sorghum managed for biofuel. Agric. Wat. Man. 155:40-47.

Chapter 3 - Evaluation of Corn and Forage Sorghum Production Hoxie, Kansas.

Introduction

Another research location was chosen to gain further appreciation of the differences between corn and forage sorghum. A second location was selected in Sheridan County, Kansas, near the town of Hoxie. The location was selected due to some of its traits. This location was important due to its high agricultural productivity. Sheridan County is located in the northwest portion of Kansas and sits on top of the Ogallala Aquifer which is the largest aquifer in Kansas. Sheridan County sold $328,685,000 in agricultural commodities namely crops and livestock in 2012 (NASS, 2012). Data from NASS (2012) noted Sheridan County having 123,299 acres of corn and 117,073 head of cattle in 2012. The high number of cattle is a driver for corn for feed. Of those corn acres 53,000 acres are irrigated. It has been noted that irrigated corn as feed and cattle production follows groundwater use patterns (Steward, 2013). This becomes important when producers consider the decline in water levels in the aquifer (Peterson and Bernardo, 2003). Corn has been found to require large amounts of water per year for production (Marsalis et al., 2010; Howell et al., 1997). It is important to start looking at production alternatives to be able to sustain production of agricultural exports. An option to evaluate as a feed source is forage sorghum which can be grown on dry or irrigated acres. McCuistion et al. (2009) found that in even reduced irrigation schemes, forage sorghum may be an alternative roughage crop. An evaluation of forage sorghum and corn production potential in both irrigated and dryland environment would provide producers with data for which to make production decisions.

Objective

It is understood that forage sorghum can be competitive with corn for forage use in western Kansas. Biomass production, water use efficiency and feed value of both crops have been considered as decision making factors for producers interested in forage production. An evaluation of corn alongside photoperiod sensitive forage sorghum may give some insight on forage production that is most efficient for western Kansas. The purpose of this study was to agronomicaly evaluate biomass production, water use and also understand basic feed values that can be used for further decision making.

Materials and Methods

Site data

A field study was conducted in Sheridan County, Kansas near the town of Hoxie. The soil is a deep silt loam soil (Keith silt loam, fine-silty, mixed, mesic Aridic Argiustoll). The average summer precipitation for the region is 429 mm. The study was placed on a cooperator's field. Due to the nature of agronomic research, a structured plot design is not always achievable. The study was designed for an irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn treatment. The study was placed on the corner of an irrigation pivot. A 40 meter block of photoperiod sensitive forage sorghum (PSS) was planted from the edge of the dryland corner into the area underneath the irrigated pivot, the same was done with the corn. This allowed for large scale mechanical maintenance and harvest of the plots by the cooperator when the study was complete. This allowed for 4 treatment areas, irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn. Biomass sampling, water analysis and solar radiation data were all done within representative locations within the treatment. A plot map can be found in Appendix B-4. In 2013, the irrigation system was nozzled so that the innermost span of the system received no water making it a dryland location and the outer spans were used as an irrigation treatment. The corn and forage sorghum were planted in a similar fashion as the previously mentioned design. A plot map of the design can be found in Appendix B-5. The corn was planted on 5 May 2011, 5 May 2012 and 6 May 2013. The corn variety was Pioneer 35F48 (Pioneer) and was planted at a density of 45,000 plants ha^{-1} for dryland plots and 79,000 plants ha^{-1} for irrigated plots. The PSS was planted 3 June 2011, 29 May 2012 and 30 May 2013 and the variety was 1990 (Sorghum Partners) and was planted at a density of 99,000 plants ha^{-1} for dryland plots and 173,000 plants ha^{-1} for irrigated plots. Pre-emergence herbicides were applied to all treatments for weed control. Plots were irrigated with a central pivot sprinkler irrigation system. Growing degree days (GDD) were calculated with an upper temperature threshold of 30°C for corn and 38°C for forage sorghum using a base temperature of 10°C (McMaster and Wilhelm, 1997). The initial position of the GDD line on Figure 2-2, 2-3 and 2-4 is the initial accumulation of GDD after planting. Temperature data were collected from a weather station at Colby, Kansas. Rainfall and irrigation data were collected on site.

Harvest and material handling

One meter of row (0.762 m^2) above ground biomass harvests were taken five times over the growing season (Table 3-1). Plants in a randomly selected linear meter of row were harvested 3-6 cm above the soil surface. Biomass was then dried at 60 C for 10 days and weighed. On the last day of harvest corn ears were separated from the stalk, mechanically shelled, dried at 60^{o}C for a minimum of 72 hours and weighed. Grain yield was adjusted to 0.155 g g^{-1} moisture (wet basis). Total biomass was reported as sum of the stover, cob and grain on a dry matter basis. Harvest index was calculated by dividing dry grain yield by total dry above ground biomass. A fresh sample was taken to a laboratory (Servi-Tech Labs, Dodge City, KS) the day of harvest for nutrient analysis. Samples at the lab were dried and then ground. Crude protein content was taken using methodology found in AOAC (2012). Acid detergent fiber was evaluated according to Ankom (2006). Neutral detergent fiber was evaluated according to Ankom (2006). Nitrate content was taken using methods described by Cataldo et al. (1975). Prussic acid was taken using methods described by Gillingham et al. (1969).

Soil Water

Soil water was determined using a neutron probe (Model 503DR Hydroprobe Moisture Depth Gauge, Campbell Pacific Nuclear, CA.). The probe was field calibrated as described by Evett and Steiner (1995). Calibration was initiated with gravimetric water content that was determined from soil samples centered at 30 cm increments to 244 cm. Gravimetric water content was determined from soil cores (15.24 cm long and 2.84 cm in diameter) obtained with a hydraulic probe. Bulk density cores (15.24 cm long and 2.84 cm in diameter) were also obtained using a hydraulic probe. Bulk density data are found in Appendix B-6. To calculate volumetric water content from the neutron probe counts, gravimetric water content from samples was multiplied by dry bulk density for a specific sampling depth. Cores used for gravimetric measurements were also used for bulk density measurements. Neutron probe counts were taken from each depth so that each volumetric value had a corresponding neutron probe count. Output counts were then divided by a standard count to get count ratio. A linear regression using PROC GLM of SAS (version 9.1, SAS Institute Inc., Cary, N.C.) was developed for count ratio as the independent (X) variable and soil water content as the dependent variable (Y). The developed equation was:

$$\textbf{Equation 4: } Y = 3.3028x - 0.9923$$

with a sample size of (n) = 48 and coefficient of simple determination (r^2) = 0.783. The equation was developed for inches per foot and soil water values were then converted to mm per 30.5 cm. Neutron probe readings were taken at each biomass harvest date. To attain a sampling depth of 244 cm, neutron access tubes were installed in the center of each plot and inserted to a depth of 300 cm so that there was no opportunity for the neutron probe to come in contact with soil in the bottom of the access tube.

Unavailable water contents at 1.5-MPa matric potential were performed to methods similar to that described by Klute (1986). A 15-bar porous ceramic plate SEC (Soilmoisture Equipment Corp.; Santa Barbara, CA) was used in a 15 bar SEC extractor for measurements at 1.5 MPa. Air dry soil was ground by mortar and pestle and packed into plastic rings (1 cm tall and 5 cm in diameter) so that the material was level with the top of the ring. Bulk density was not controlled when filling the rings. Rings filled with soil were then placed on the ceramic plate. Soil inside the rings were then saturated by immersing the plate in a 5m*M* $CaSO_4$ solution for 24 hours. This solution helps in minimizing dispersion of clays in the soil. Samples were removed from the extractor after a 7 day equilibration time. Samples were immediately removed from the plates, weighed, dried for 24 hours at 105°C and then re-weighed to determine gravimetric water content. Means from multiple runs per sampling depth were used as unavailable soil water values for a specific depth. From these values the profile was shown to have 361 mm of unavailable water in a 244 cm soil profile. Stone et al. (2011) found 388 mm of unavailable water on a Keith silt loam soil in the same region. Water use or evaportranspiration

(ET) was calculated by summing irrigation, rainfall and change in soil water content from the first sample date to the last sample date minus drainage. Available profile water content was calculated as summing soil water contents at each depth minus unavailable soil water. Drainage was then subtracted from that total.

Drainage was calculated using a Wilcox-type drainage equation developed from Stone et al. (2011). The drainage equation was used to evaluate drainage at the 244 cm depth. Drainage was found in 2011 in irrigated plots. The range for total season drainage for irrigated corn plots was 87 mm to 101 mm and 52 mm to 83 mm for forage sorghum plots.

Water use efficiency of biomass (WUE_b) was calculated as above ground biomass (kg ha^{-1}) divided by seasonal water use (mm). Water use efficiency of corn grains (WUE_g) was calculated as dry corn grain (kg ha^{-1}) divided by seasonal water use (mm).

Light interception

Light interception data were collected with a LAI-2000 (LI-COR, Inc., Lincoln, NE) which recorded measurements from a 1 m line quantum sensor (Model LI-191SB, LI-COR, Inc., Lincoln, NE). Photosynthetically active radiation (PAR) was measured by placing the sensor perpendicular to the row, centered on the row, at the soil surface under the plant canopy. A measurement of incident PAR was taken immediately outside of the canopy. An inside the canopy and outside the canopy measurement was taken for each plot. Intercepted photosynthetically active radiation (IPAR) could then be calculated by dividing the below canopy measurement by the outside of the canopy measurement. Growing degree days were calculated using 30°C as maximum daily high temperature for corn and 37.7°C for forage sorghum.

Data analysis was done in using PROC MEANS in SAS (version 9.1, SAS Institute Inc., Cary, NC). Means and standard errors were computed for all samples taken for each treatment PROC GLM in SAS (version 9.1, SAS Institute Inc., Cary, NC) was used for linear regression.

Results

Weather

Long term precipitation and reference ET.

The weather data for the Hoxie location are presented in Table 3-2. In 2012, there was less precipitation than in 2011 and 2013, while 2011 had the most precipitation of the 3 years. The 3 study years were lower than the long term average. The reference evapotranspiration (ET) is presented in Table 3-2 as a mean daily value during each month. The reference ET demand was higher in the growing season during 2012 than 2011 and 2013. Long term weather data were extracted from the High Plains Regional Climate Centers web site (HPRCC). The daily ET values used for mean calculation were extracted from the Kansas State University, Research and Extension Weather Data Library (KSUREWDL).

Average daily temperature

Average daily temperatures are presented in Figure 3-1. The year 2011 saw cooler growing season temperatures than 2012 and 2013. The warmest temperatures appeared to be in 2012. Maximum and minimum temperatures for the growing season are presented in Appendix B-1, B-2 and B-3.

Growing degree days 2011

The GDD for 2011 are presented in Figure 3-2. The corn accumulated GDD faster in the growing season due to an earlier planting date. Forage sorghum was able to quickly accumulate GDD due to a higher maximum GDD equation growth temperature and ended the season with close to the same amount of GDD as corn. The corn initiated silking in early July and reached physiological maturity in early September.

Growing degree days 2012

The GDD for 2012 are presented in Figure 3-3. The corn accumulated GDD faster in the growing season due to an earlier planting date. Forage sorghum was able to quickly accumulate GDD due to a higher maximum GDD equation growth temperature and ended the season with the same amount of GDD as corn. The corn in 2012 was initiating silking at a time of heat stress as shown in Figure 3-1 and Appendix 1. The corn reached physiological maturity in early September.

Growing degree days 2013

The GDD for 2013 are presented in Figure 3-4. The corn accumulated GDD faster in the growing season due to an earlier planting date. The corn initiated silking in early July and reached physiological maturity in early September.

Irrigation amounts

Irrigation amounts by month for 2011, 2012 and 2013 are presented in Table 3-3. Measured irrigation amounts are similar through the three study years. July of 2012, saw the most irrigation with 163 cm while October of 2011 saw the least with 33 cm.

Biomass

End of season biomass for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn is presented in Table 3-4. Irrigated forage sorghum produced higher biomass than irrigated corn for the years of the study with corn and forage sorghum being similar in 2013. The largest numerical difference occurred in 2012, where irrigated forage sorghum yielded 12 Mg ha^{-1} more than irrigated corn. Also in 2012, there was the largest difference between dryland forage sorghum and dryland corn. The dryland forage sorghum yielded 6 Mg ha^{-1} more than dryland corn. This can be attributed to high temperatures as well as reduced rainfall during the 2012 growing season. Since the forage sorghum was photoperiod sensitive it did not go through a stressful reproductive period like corn went through. The forage sorghum was able to remain in a vegetative stage and endure the stressful period better than the corn, which is driven by heat units, therefore maturing faster in warmer temperatures. Dryland corn yields were also low in 2013.

Corn grain yield and corn harvest index are presented on Table 3-5. Irrigated corn grain yield was highest in 2011. In 2011, there was adequate rainfall and temperatures that were not stressful to plant performance. Irrigated corn saw its lowest yields in 2012 which experienced heat stress as well as drought stress during reproductive phases of plant development. Dryland corn yields followed a similar trend with the highest yields in 2011 and lowest in 2012. Harvest indices were higher than other reported harvest indices. This was due to harvesting the corn well beyond physiological maturity where it has been exposed to natural desiccation and weathering.

Biomass accumulation for irrigated corn, irrigated forage sorghum, dryland corn and dryland forage sorghum in 2011 is presented in Figure 3-5. In 2011, irrigated corn had the most rapid biomass accumulation due to early planting date and early accumulation of GDD but yielded slightly less than forage sorghum at the end of the year. Irrigated forage sorghum had a constant increase in biomass over the season. Dryland forage sorghum also steadily increased in biomass over the season but at a slower rate.

Biomass accumulation for irrigated corn, irrigated forage sorghum, dryland corn and dryland forage sorghum in 2012 is presented in Figure 3-6. Irrigated corn and dryland corn followed the same trend with an increase in biomass accumulation until early August and then saw a reduced yield in the middle of September. This can be attributed to high temperatures and low precipitation. The irrigated forage sorghum increased biomass accumulation through the growing season along with dryland forage sorghum.

Biomass accumulation for irrigated corn, irrigated forage sorghum, dryland corn and dryland forage sorghum in 2013 is presented in Figure 3-7. Irrigated corn and irrigated forage sorghum both followed a similar trend in biomass accumulation in 2013. In 2013, the growing season experienced higher precipitation amounts than 2012 as well as lower average temperatures after corn initiated silking.

Soil water and water use efficiency

Available soil water by depth for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn for 2011 is presented in Table 3-6. The means of the available soil water show that as the season progressed the irrigated forage sorghum and irrigated corn was able to maintain more volumetric water at deeper depths than dryland forage sorghum and dryland corn. The dryland forage sorghum and the dryland corn both saw a reduction in soil available water noticeably in the top six depths from 4 August to 4 September. During this period dryland corn and dryland forage sorghum were experiencing growth as seen in Figure 3-5 and were only getting benefit of rainfall versus the irrigated treatments which received rainfall and irrigation.

Available soil water by depth for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn for 2012 is presented in Table 3-7. The dryland sorghum and dryland corn treatments both saw reduction in available soil water content through the top seven depths between 14 July and 18 September. That period was under heat stress as well as during a phase of growth. The irrigated sorghum and irrigated corn also saw a reduction in available soil water during this period though it did not get as dry as the dryland plots.

Available soil water by depth for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn for 2013 is presented in Table 3-8. The available water in the profile in the early part of the growing season is less than it was in the previous year following a warm year and less than average precipitation.

Available soil water across dates in the 244 cm profile by date is presented in Table 3-9. In 2011, irrigated forage sorghum and dryland sorghum tended to have less water in the profile than their corn counterparts. This was due to forage sorghum still growing and corn having reached physiological maturity and dried down. Dryland forage sorghum had a noticeable reduction in available soil water from the first sampling period to the last, due to only being able to replenish the available soil water with rainfall versus having added irrigation. Dryland corn had a noticeable difference between the 4 August and 4 September sample dates.

Available soil water in the 244 cm profile by date from 2012 is presented in Table 3-10. In 2012, all plots saw dramatic decreases in soil water across the growing season. This can be attributed to heat stress and drought stress during the growing season. Irrigated forage sorghum saw the largest decrease with a 216 mm decrease in available water from the first sampling date to harvest. Dryland corn saw the least decrease in available water from the first sampling period to harvest with 125 mm.

Available soil water in the 244 profile by date from 2013 is presented in Table 3-11. In 2013, all treatments saw a reduction in available profile water on 23 July. This can be attributed to growth of the forage sorghum and the initiation of silking in the corn. Available soil water increased for the next two sampling dates except the irrigated forage sorghum which showed a decrease on the last sampling date, this could be linked with growth.

End of season water use is presented on Table 3-12. In 2011, irrigated forage sorghum water use was very similar to irrigated corn water use. Also that year, dryland corn water use was less than dryland forage sorghum water use. In 2012, irrigated forage sorghum used more water than irrigated corn. Dryland forage sorghum again used more water than dryland corn. Similar to 2012, in 2013 irrigated forage sorghum had higher water use than irrigated corn. Again in 2013, dryland forage sorghum had higher water use than dryland corn. Dryland corn water use was low in 2013 and could be attributed to poor plot conditions.

End of season biomass water use efficiency is presented in Table 3-13. Irrigated forage sorghum was very consistent in biomass water use efficiency for all 3 years. Irrigated corn water use efficiency was lower than irrigated sorghum in 2012 but higher in 2013. This was likely due to the drought and heat stress conditions in 2012 and a less stressful growing season in 2013. Dryland forage sorghum exhibited the highest biomass water use efficiency in 2013 for any treatment of any year. Dryland corn water use efficiency for 2013 was also very high.

Corn grain water use efficiency is presented in Table 3-14. Corn grain water use efficiency followed the same trend as the corn biomass. In 2012, there were noticeably lower corn grain yields due to heat and drought stress during reproductive phases. In 2013, the dryland corn had lower yields than expected for less stressful growing conditions than were in 2012.

Hoxie biomass versus water use for 2011, 2012 and 2013 are presented in Figure 3-8. A linear regression was developed for this data. A liner regression equation was developed by using PROC GLM of SAS (version 9.1, SAS Institute Inc., Cary, N.C.) with water use (millimeters) the independent (X) variable and the biomass (kilograms per hectare) the dependent variable (Y). The biomass versus water use biomass equation for forage sorghum is:

Equation 5 $$Y= 0.37+0.026X$$

where sample size (n)=24, and coefficient of simple determination (r^2) = 0.874. The same equation was developed for corn and it is given as follows:

Equation 6 $$Y=0.58+0.019X$$

where sample size (n)=24, and coefficient of simple determination (r^2) = 0.551. The forage sorghum biomass accumulation slope shows a greater increase per unit of water than corn.

Light interception

Light interception values for Hoxie, Kansas 2011, are presented in Table 3-15. In 2011, corn captured more PAR earlier in the season than forage sorghum for both irrigated and dryland treatments due to earlier planting date. On 4 August, forage sorghum had captured a similar amount of PAR as corn for all treatments. At harvest, corn had reduced its captured amount of PAR while forage sorghum was still capturing 80% or more in both irrigated and dryland treatments.

Light interception values for Hoxie, Kansas, 2012, are presented on Table 3-16. In 2012, irrigated and dryland corn captured more PAR earlier in the season than irrigated and dryland forage sorghum. Forage sorghum exceeded corn in the amount of PAR that it was capturing on the 14 July sampling date. Forage sorghum continued this trend until the end of the season.

Light interception values for Hoxie, Kansas 2013, are presented in Table 3-17. In 2013, Irrigated corn captured more PAR than irrigated forage sorghum on the 28 June and 9 July sampling dates. Irrigated forage sorghum continued to capture more PAR than corn for the rest of the season. PAR values for irrigated corn and irrigated forage sorghum were most similar on the 23 August sampling date. Dryland corn saw a decrease in intercepted photosynthetically active radiation (IPAR) from 28 June to 9 July. This could be due to sampling error. Dryland corn increased IPAR until 23 August then it decreased to the 20 September sampling date. Dryland forage sorghum continued to capture over 0.90 of PAR on 23 August and 20 September.

Nutritional values

Nutritional values for Hoxie, 2012, are presented in Table 3-18. The crude protein content of the irrigated treatments were numerically different in irrigated forage sorghum and dryland forage sorghum. Dryland forage sorghum had lower ADF values than irrigated forage sorghum. The NDF values of irrigated forage sorghum were higher than dryland forage sorghum values. Irrigated forage sorghum had higher levels of prussic acid than dryland forage sorghum. Dryland forage sorghum had higher concentration of nitrates than irrigated forage sorghum. Irrigated corn had lower levels of crude protein than dryland corn. Irrigated corn had higher levels of ADF than dryland corn. Irrigated corn had higher levels of NDF than dryland corn. Prussic acid was very low for both dryland corn and irrigated corn. Irrigated corn had the highest level of nitrate with 3385 mg kg^{-1}.

Nutritional values for Hoxie, 2013, are presented in Table 3-19. Irrigated forage sorghum and slightly lower levels of crude protein than dryland forage sorghum. Irrigated forage sorghum had higher ADF and NDF than dryland forage sorghum. Irrigated forage sorghum had lower levels of prussic acid and nitrate than dryland forage sorghum. Irrigated corn had slightly less crude protein than dryland corn. Irrigated corn had higher ADF and NDF values than dryland corn. Irrigated corn had more nitrate than dryland corn.

Discussion

Biomass

Biomass production was one of the primary objectives of the research. Corn biomass accumulation started earlier in the spring due to an earlier planting date than forage sorghum. In 2011 and 2013, irrigated forage sorghum biomass accumulation did not meet irrigated forage sorghum biomass accumulation until close to 1 October. In contrast forage sorghum exceeded irrigated corn growth in early August in 2012. This difference was due to the stressful growing conditions in 2012, where rainfall was below average and initiation of silking was in a period of high temperatures. Other researchers have found high temperatures at vegetation can reduce yields by 25%, high temperature stress at silking can decrease yields as high as 50% and high temperature after stress can reduce yields by 21% (Denmead and Shaw, 1960). Irrigated sorghum yielding higher than dryland sorghum is expected and observed by other researchers (Weichenthal et al., 2003; McCuistion et al., 2009). Dryland corn yields in Hoxie also suffered from stressful conditions. Irrigated forage sorghum had its highest yield in 2012. This agreed with results found by Bean et al. (2013), that showed a similar yield for forage sorghum in a below average year but contrasts with Yohannas (2015) who found the highest yielding year of a three year study to be the one with the most rainfall. Other researchers have found photoperiod sensitive sorghum to yield well under full irrigation and under dryland conditions (Hao et al., 2014). Dryland corn yields were highest in 2011 due to good growing conditions and lowest in 2012 when growing conditions were stressful. The dryland corn yields were also low in 2013 when growing conditions were not stressful and that is due to pre-existing poor plot conditions that existed without researcher knowledge. Dryland corn grain yields followed the same trend with 2011 being the highest yielding year and 2012 being the lowest yielding year. The irrigated corn grain yield mean was in agreement with a 10 year mean of fully irrigated corn reported by Schlegel and Havlin (1995). Harvest index numbers were higher than reported by others (Olsen, 1971). The harvest index numbers were high due to a longer period of time between physiological maturity and harvest. The plants were exposed to natural degradation and weathering which caused a loss of vegetative material.

Water use and water use efficiency (WUE) of biomass and grain production.

Growing season water use ranged from 675 mm to 207 mm for forage sorghum and 666 mm to 134 mm in corn. Dryland forage sorghum was able to achieve similar biomass yields with varying levels of water use which was also found by other researchers (Tolk and Howell, 2003). The dryland sorghum was able to grow consistent yields, within 1.2 Mg ha^{-1} across a range of water use from 365 mm to 207 mm. Water use was highest for irrigated forage sorghum in 2012 which had a stressful growing season but the irrigated forage sorghum was able to grow the largest biomass yield for the 3 year study, which shows that irrigated forage sorghum was able to maintain the same WUE$_b$ in a stressful year as it did in 2011 and 2013. Sorghum WUE$_b$ ranged from 23.15 kg ha^{-1} mm^{-1} to 36.46 kg ha^{-1} mm^{-1}. These ranges are slightly lower than those found by Hao et al. (2014). Corn WUE$_b$ and WUE$_g$ were in agreement with previous work (Hattendorf, 1988). Irrigated corn in 2013 had the highest level of WUE$_b$ and WUE$_g$ of corn which can be related to less stressful growing conditions than 2012. Tolk and Howell (2003) found that generally corn shows high WUE and lower water use in mild weather conditions which is what was observed here. Dryland corn yields were affected by the poor growing conditions in 2012 and poor plot conditions in 2013. In 2011, the dryland corn WUE$_g$ was higher than any other year but also had the most error in sampling. The biomass versus water use data (Figure 3-8) shows a greater increase in biomass per unit of water for forage sorghum than corn. According to the equation, forage sorghum can produce 2.6 Mg ha^{-1} with each additional 100 mm of water use which is slightly higher than corn which shows an increase of 1.9 Mg ha^{-1} for each additional 100 mm of water use. The r^2 value for corn is quite low compared to sorghum and can be explained by poor yields in the stressful year of 2012 causing variation in the yields. Other researchers in Texas have found an even larger increase in biomass production per each additional 100 mm of water for a photoperiod sensitive sorghum at 4.4 Mg ha^{-1} (McCuistion et al., 2009).

Soil water

In 2011, the available soil water by depth data and the available soil water for the 244 cm profile for the irrigated treatment tend to show little change from 4 July to 16 October. This is possible by 384 mm of precipitation from April to October as well as mild temperatures. The dryland treatments available soil water by depth data coincided nicely with the total available soil profile water data and showed a decrease across time for dryland forage sorghum. Dryland corn however showed an addition to the soil profile water at 16 October which could be due to precipitation that is not being used because of senescence.

In 2012, the irrigated treatments showed drying at all depths on 18 September. The total available profile also showed that the profile was much dryer on 18 September than any other date. This was due to a stressful growing conditions, irrigation and rain water not being able to replenish the profile fast enough. The dryland treatments also showed a reduction in available profile water from 11 June to 18 September.

In 2013, similar to 2011 and 2012, there were numerical differences between available soil water contents by depth, treatment and across sampling dates. Available profile soil water was much lower in the irrigated treatments than any other year. This could be due to conditions prior to 2013. The dryland treatments had more profile available water which could be due to the dryland plot area being previously irrigated in 2012. Dryland forage sorghum does show a decrease in profile available water across all sampling dates. Irrigated forage sorghum, irrigated corn and dryland corn all show intermittent increases in profile available water from rainfall and irrigation events. For dryland forage sorghum, a steady decrease in profile available water through the season does suggest growth and helps to illustrate its WUE_b which in 2013 was higher than any other treatment at 36 kg ha^{-1} mm^{-1}.

Light interception

Light interception for 2011, 2012 and 2013 all show a trend for differences. In all years corn intercepted more light faster than sorghum in both irrigated and dryland treatments. This increase in light interception was also seen in the early season growth in Figure 3-15, 3-16 and 3-17. In all years, corn also decreased its interception of PAR at the end of the season due to the physiological maturation of the corn while the sorghum was still growing. Forage sorghum growing after the corn had reached physiological maturity can be seen by the biomass accumulation data as well as the high amount of IPAR on the last sampling date of all years. The data tends to agree with Muchow et al. (1990) who found that under favorable growing conditions, biomass accumulation is directly proportional to the amount of radiation intercepted.

Nutritional values

Nutritional values were collected at the end of the season to get an idea of the nutritional quality of the plant material. Crude protein was evaluated because it is a common parameter in animal feed. Crude protein of the corn stover and forage sorghum was tested to determine what the differences were in just the vegetative material. Because of logistics, we were not able to take digestibility data on the samples, therefore comparisons will be made within species only for all nutritional values. In 2012, crude protein contents were higher for dryland forage sorghum than irrigated forage sorghum. Dryland forage sorghum crude protein values were also higher in 2013 than irrigated forage sorghum. Dryland forage sorghum crude protein was higher than irrigated forage sorghum in 2012 and 2013. McCusition et al. (2010) found that crude protein content in photoperiod sensitive sorghums tend to decrease with yield which was in agreement with the results Dryland corn stover crude protein was also higher in 2012 and 2013 than irrigated corn stover. Corn stover crude protein values tend to agree with Lauer et al. (2000) and McCuistion et al. (2010).

Acid detergent fiber (ADF) is a component of NDF which represents fiber in the plant, and ADF is composed of cellulose and lignin which have been shown to limit digestion (NRC 2001). Irrigated forage sorghum had a higher ADF value than dryland forage sorghum in both years of the study. Forage sorghum ADF values were in agreement with Cummins (1981).Irrigated corn followed a similar trend with higher ADF values in 2012 and 2013 than dryland corn. Corn ADF values agreed with Crasta et al. (1997).

Neutral detergent fiber (NDF) was evaluated to determine the amount of hemicellulose and other neutral detergent solubles in the plant. In 2011 and 2012 irrigated forage sorghum had a lower NDF values than dryland forage sorghum. The NDF values for forage sorghum were similar to those found by McCuistion et al. (2010). Irrigated corn stover also had higher NDF values than dryland corn in both years of the study. Irrigated corn stover NDF values were higher in 2012 which was hot and dry and agrees with a similar trend found by Cox et al. (1994)

Prussic acid which is also known as hydrocyanic acid, was evaluated to determine if toxic levels of the compound existed. In both study years, forage sorghum contained more prussic acid than corn in both treatments. Forage sorghum has been shown to release prussic acid in stressful environments (Wheeler et al., 1990). Prussic acid concentration was highest in 2012 which was due to stressful conditions and levels reported could be toxic for some animals (Egekeze and Oehme, 1980).

Nitrate content was evaluated to determine if toxic levels existed in the plant material. Numerical differences existed amongst all treatments. High nitrate content in plants have been found to be toxic and fatal to livestock (Harms and Tucker, 1973). Nitrate levels in irrigated corn in 2012 and 2013 were higher than levels in dryland corn. Irrigated forage sorghum had lower levels of nitrate in both years of the study than dryland forage sorghum. This could be due to excess fertility and stress as suggested by Harms and Tucker (1973).

Due to the nature of the research, corn was not able to be sampled on a representative date that it would be taken for corn silage. The corn samples taken represent a stover harvest.

Samples taken to represent silage must also undergo an ensiling process to get a correct representation of the nutrients. The difference in nutritive values will change based on harvest date. Corn has an earlier maturity date than the photoperiod sensitive forage sorghum. Harvest date must be taken into consideration when evaluating nutritional values.

Conclusion

The forage sorghum overall tended to yield more biomass than corn. Dryland forage sorghum also used more water than dryland corn. Irrigated forage sorghum used the same or more water than irrigated corn. Though the irrigated forage sorghum and the dryland forage sorghum used more water, they also grew more biomass which increased their water use efficiency. Water use efficiency was higher for forage sorghum when compared with corn in all years except in 2013 when irrigated corn proved to be more water use efficient than irrigated forage sorghum. One of the ways forage sorghum was able to be water use efficient was never undergoing reproductive stress during the growing season and the forage sorghum also grew better in warmer temperatures as shown by the increase in maximum daily growing temperature of 38 ^{o}C for sorghum and 30 ^{o}C for corn for growing degree days. This is clear in 2012 when conditions are stressful. Forage sorghum was able to yield well in above average temperatures. The forage sorghum was also able to take advantage of late season rainfall and irrigation that happened after the corn plant had progressed through grain fill and was drying down Figure 3-8 illustrates forage sorghum ability to yield well and respond to water input. The corn data are not as strong, as sampling error and weather play a major role. This was also evident in the fraction of PAR, as forage sorghum continued to capture 90% of the incoming solar radiation late in the growing season. The dryland corn in 2013 was artificially low because of poor plot conditions that could not be avoided. The feed analysis data showed numerical differences of the two crops but in the case of using data for researching forage sorghum and corn, this data is acceptable values for the consideration of feeding to bovine. To get a true value for what the plant material is worth as a feedstuff, feeding trials need to be established to understand the digestibility of the material and how it reacts within the rumen before statements can be made on animal performance. Producers must have a clear understanding of their production goals and evaluate their needs for fiber or grain. Producers also must be able to understand the risks involved in the production of such crops.

Future Research

With increasing pressure on providing food and fiber for a growing population there always will be a need for more research. With the decrease in well levels in the Ogallala Aquifer we must always be conscious about the management decisions we make and how it affects production today and production for the next generation. Irrigation scheduling and irrigation methodology plays a significant role in how these crops are grown. Time and money should be invested on how to better grow crops with less water input. Forage sorghum with its high water use efficiency should be further studied to find out at what irrigation/management practices optimize production at specific locations. Variable rate irrigation is a technology that is not well understood and could help provide some answers in areas with low well capacity and need for cattle or biofuels feedstocks. Management decisions such as plant nutrition, planting architectures and weed pressure issues also may give insight on cropping system optimization. An evaluation of the sorghum genetic pool would also give us insight on where to turn to next. The end process users such as ruminant nutritionist and biofuels producers should also be considered. A replicated live bovine feeding trial with genotypes and irrigation regimes as treatment may be a quick step in the right direction. Our management practices may influence the end users saleable products and their needs met to keep all parties moving in the same direction. Harvest technologies are also needed to better prepare the plant material for the end user. Mechanical harvesting processes and chemical inoculation are also areas where very little is known how it fits into the big picture. The possibilities can be endless but the goal should be to reduce unnecessary pumping and increase crop water use efficiency to make the aquifer more sustainable for future production.

Table 3-1. Biomass harvest dates for Hoxie, Kansas.

2011	2012	2013
4 July	11 June	28 June
16 July	24 June	9 July
4 August	14 July	23 July
4 August	28 July	23 August
16 October	18 September	20 September

Table 3-2. Long-term (100 yr) temperature and rainfall means by month, mean daily reference ET by month and rainfall by month, Hoxie, Kansas 2011, 2012 and 2013.

	100-yr mean			Reference ET			Rainfall		
	Max	Min	Rain	2011	2012	2013	2011	2012	2013
	--°C--		mm	--mm d^{-1}--			--mm--		
Apr	19.3	3.0	50.2	4.8	4.5	4.3	37.8	62.2	6.6
May	24.4	8.9	80.0	6.0	6.8	6.1	46.4	11.1	36.3
Jun	30.0	14.5	77.4	8.0	9.3	8.2	38.8	6.8	48.1
Jul	33.6	17.7	77.9	7.8	8.6	7.1	119.8	60.4	60.6
Aug	32.5	16.8	66.8	6.5	6.9	5.6	67.6	25.0	84.0
Sep	27.7	11.4	41.4	4.7	5.3	5.5	7.6	16.5	96.5
Oct	21.2	4.5	35.3	4.0	3.5	3.5	66.3	16.0	20.3
Total			429.0				384.3	198.0	352.4

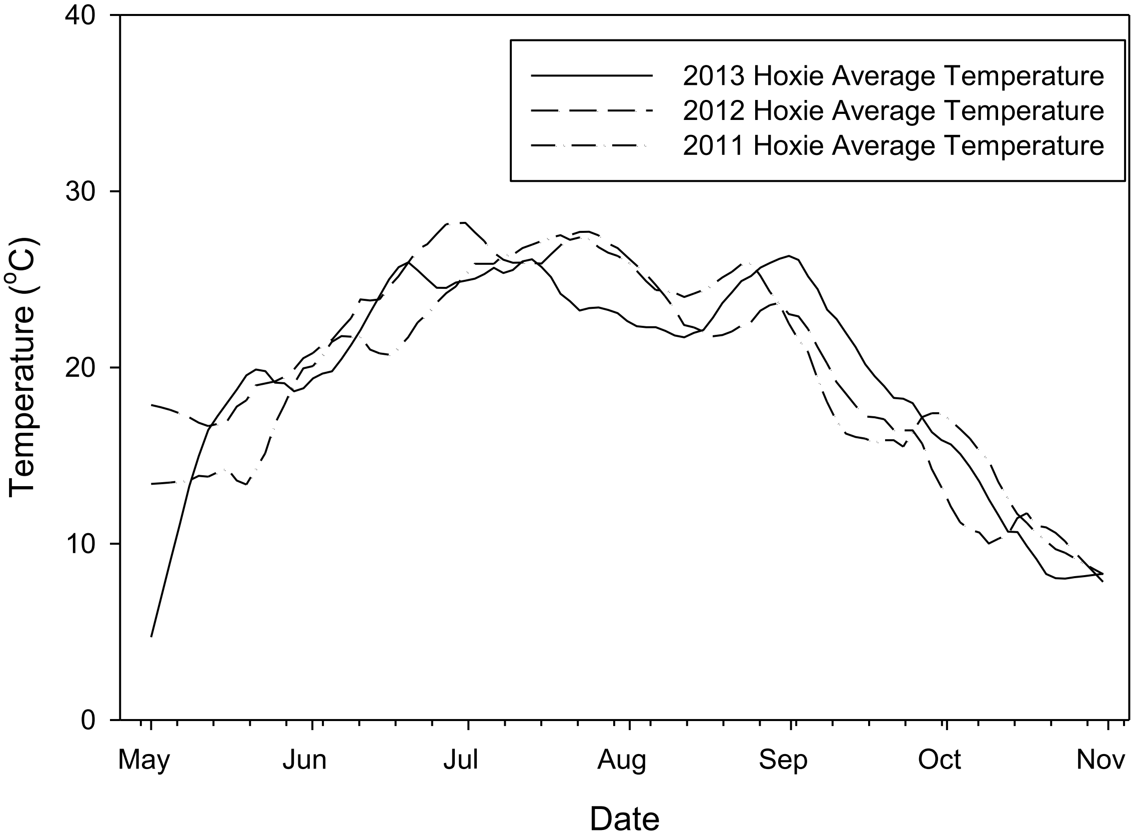


Figure 3-1. Average daily temperatures, Hoxie, Kansas 2011, 2012 and 2013.

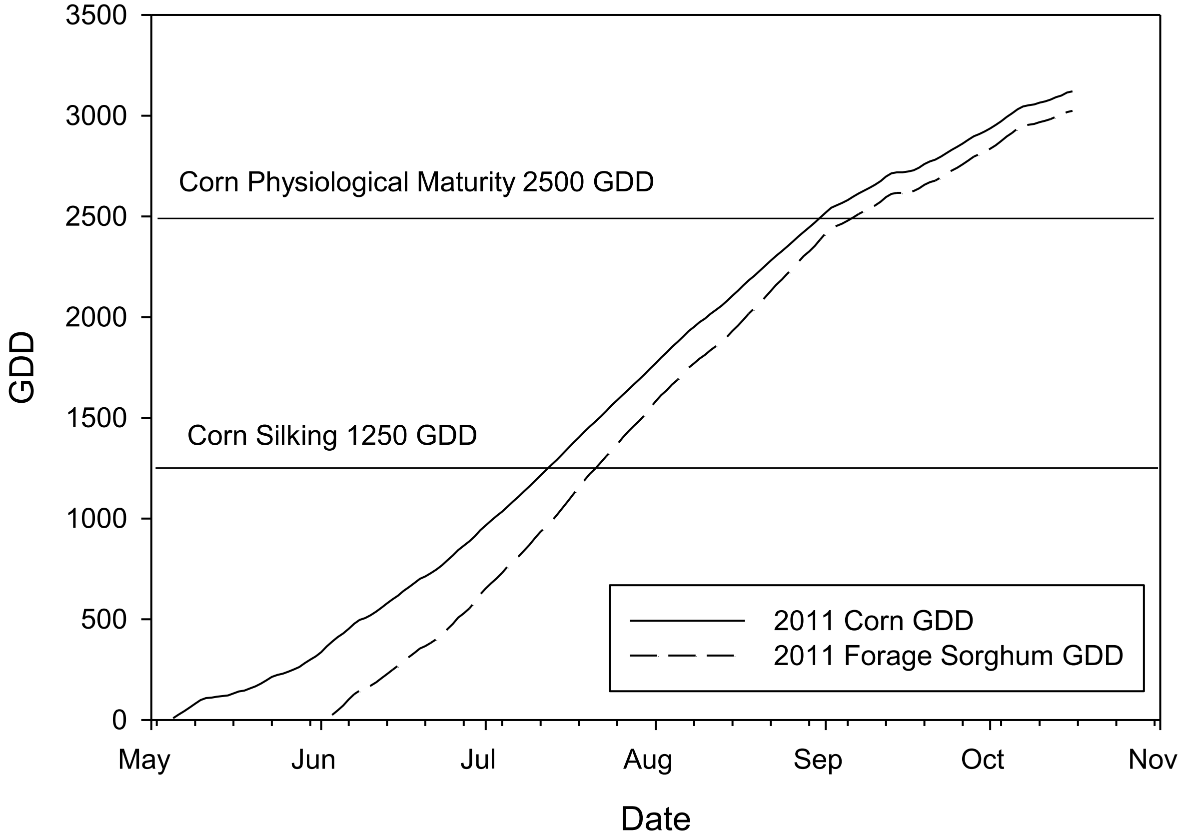


Figure 3-2. Cumulative growing degree days (GDD) for corn and forage sorghum, Hoxie, Kansas 2011.

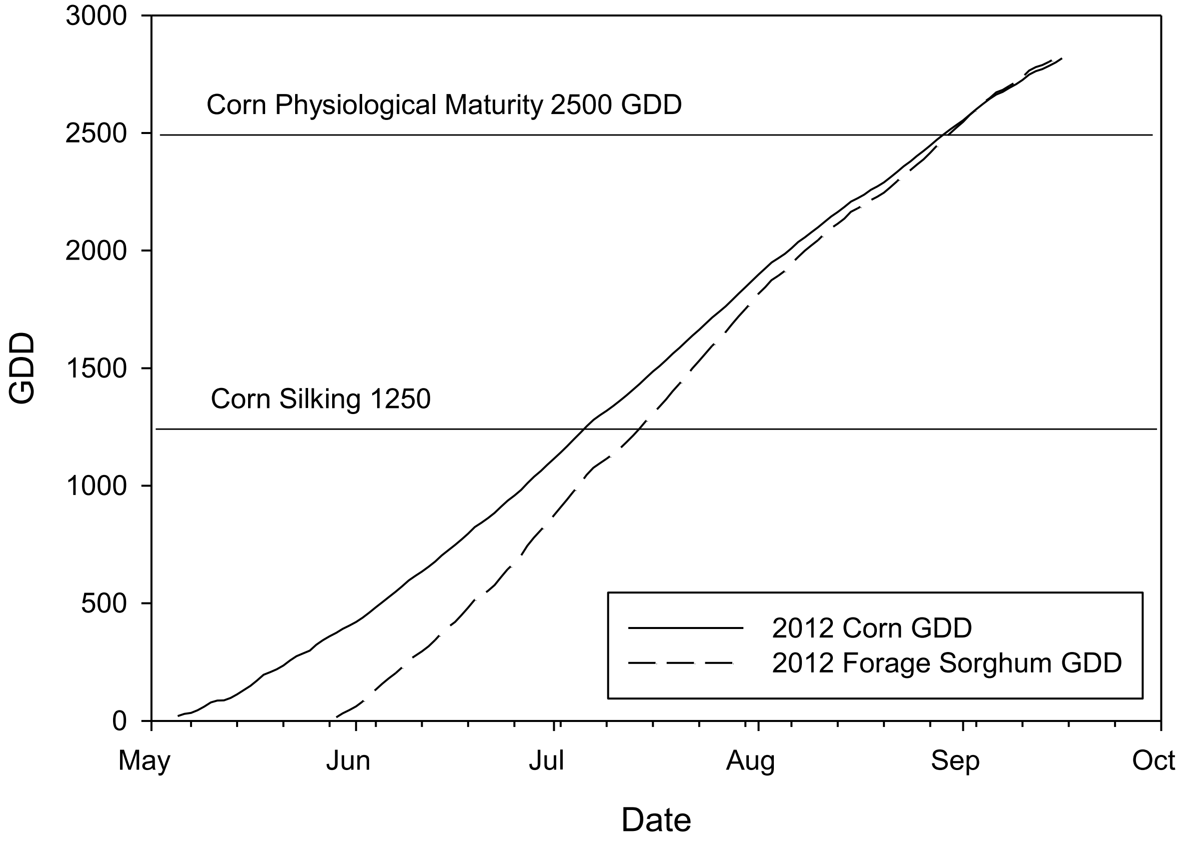


Figure 3-3. Cumulative growing degree days (GDD) for corn and forage sorghum, Hoxie, Kansas 2012.

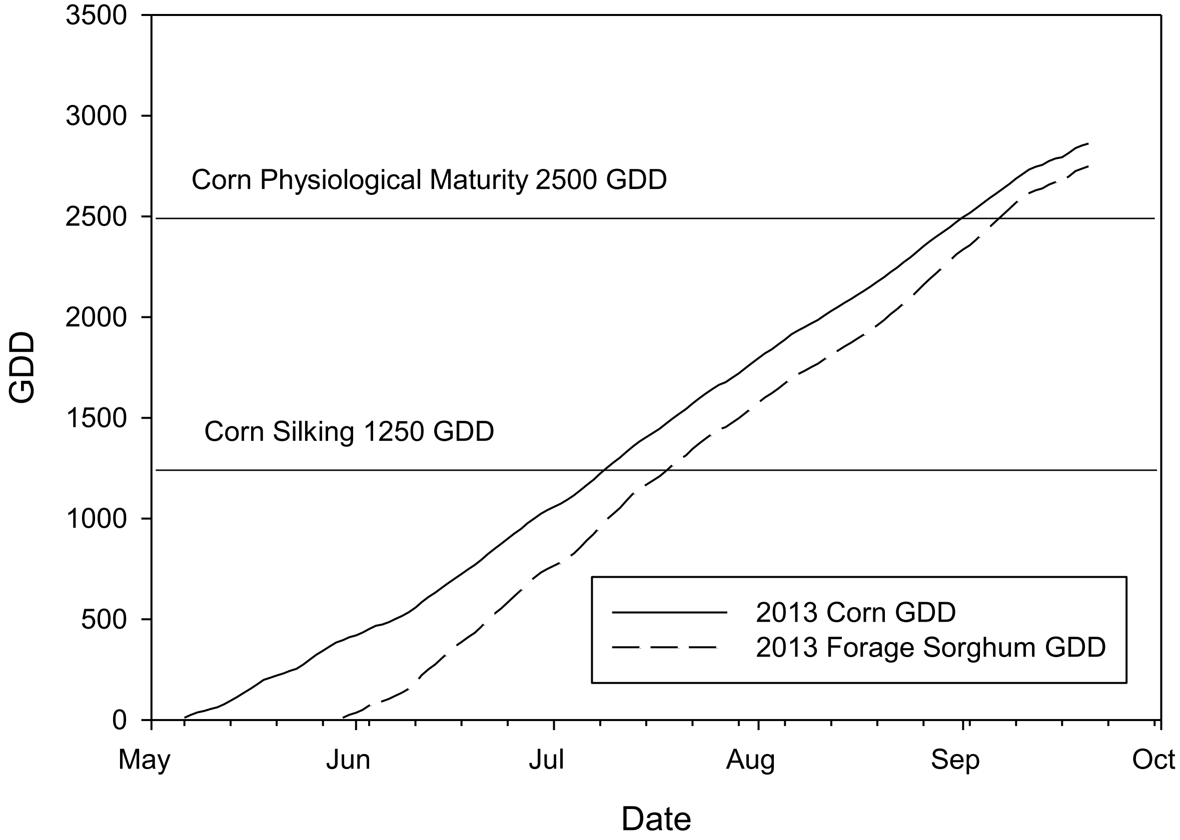


Figure 3-4 Cumulative growing degree days (GDD) for corn and forage sorghum, Hoxie, Kansas 2013.

Table 3-3. Irrigation amounts by month Hoxie, Kansas 2011, 2012 and 2013.

	2011	2012	2013
		mm	
Jun	-	36	-
Jul	134	163	101
Aug	69	130	134
Sep	132	33	129
Oct	33	-	-
Total	368	362	364

Table 3-4. End of season biomass for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn, Hoxie, Kansas 2011, 2012 and 2013.

Year	Irrigated forage sorghum	SE	Irrigated corn	SE	Dryland forage sorghum	SE	Dryland corn	SE
				Mg ha^{-1}				
2011	18.08	0.61	15.50	0.42	8.27	0.40	6.03	0.34
2012	19.00	0.33	6.640	0.54	6.86	0.52	2.59	0.22
2013	14.73	0.54	14.65	0.23	7.58	1.14	3.84	0.23

Table 3-5. Corn grain yield and corn harvest index Hoxie, Kansas 2011, 2012 and 2013.

Year	Irrigated corn grain yield	Std err	Dryland corn grain yield	Std err	Irrigated corn harvest index	Std err	Dryland corn harvest index	Std err
	kg ha^{-1}							
2011	12917.42	237.45	5046.07	236.07	0.70	0.008	0.70	0.011
2012	5096.46	391.04	1992.54	193.46	0.65	0.011	0.65	0.250
2013	12133.10	284.24	2818.94	113.06	0.70	0.015	0.62	0.015

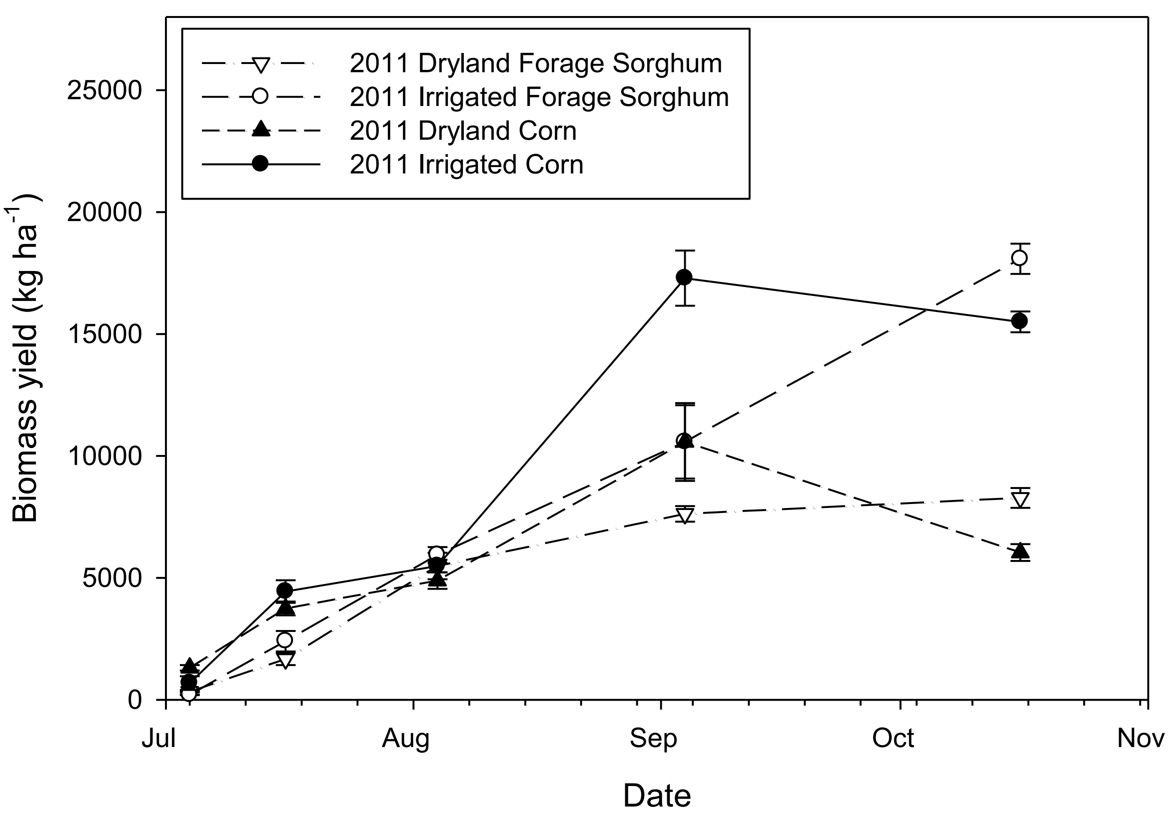


Figure 3-5. Biomass accumulation over growing season, Hoxie, Kansas, 2011.

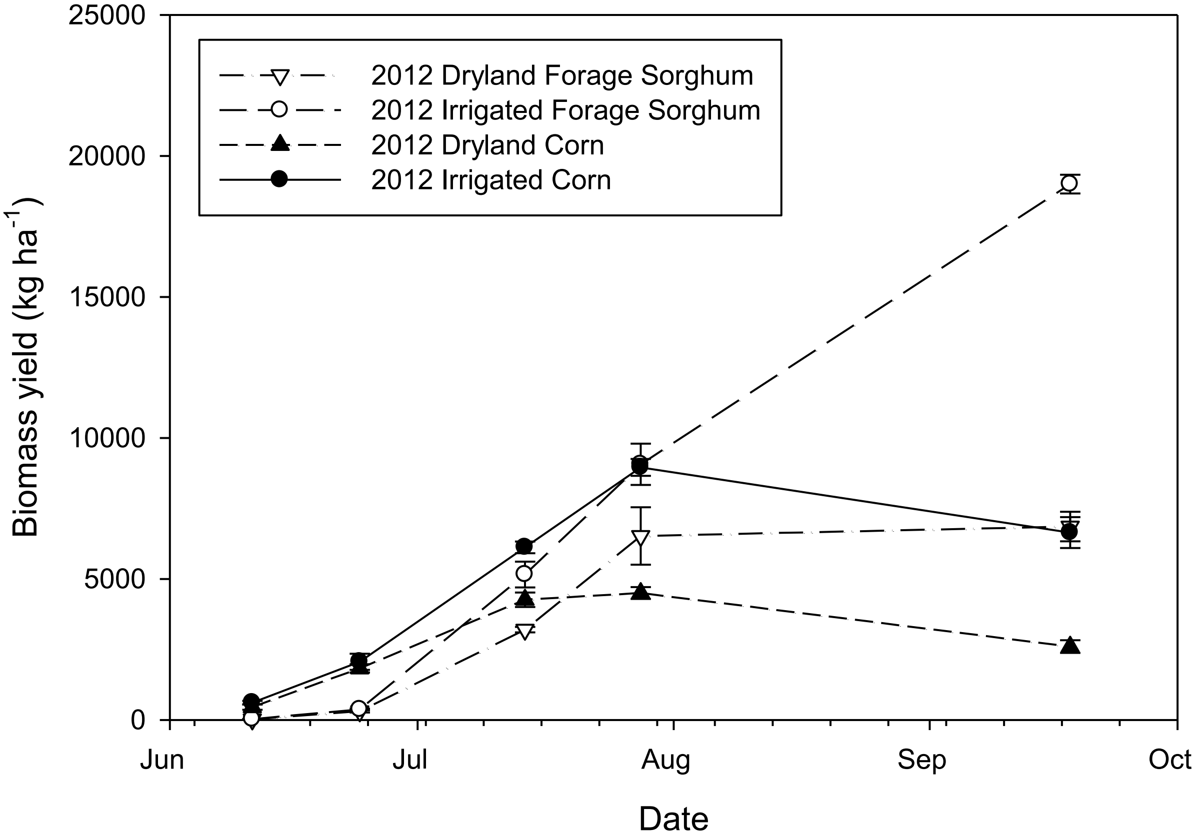


Figure 3-6. Biomass accumulation over growing season, Hoxie, Kansas 2012.

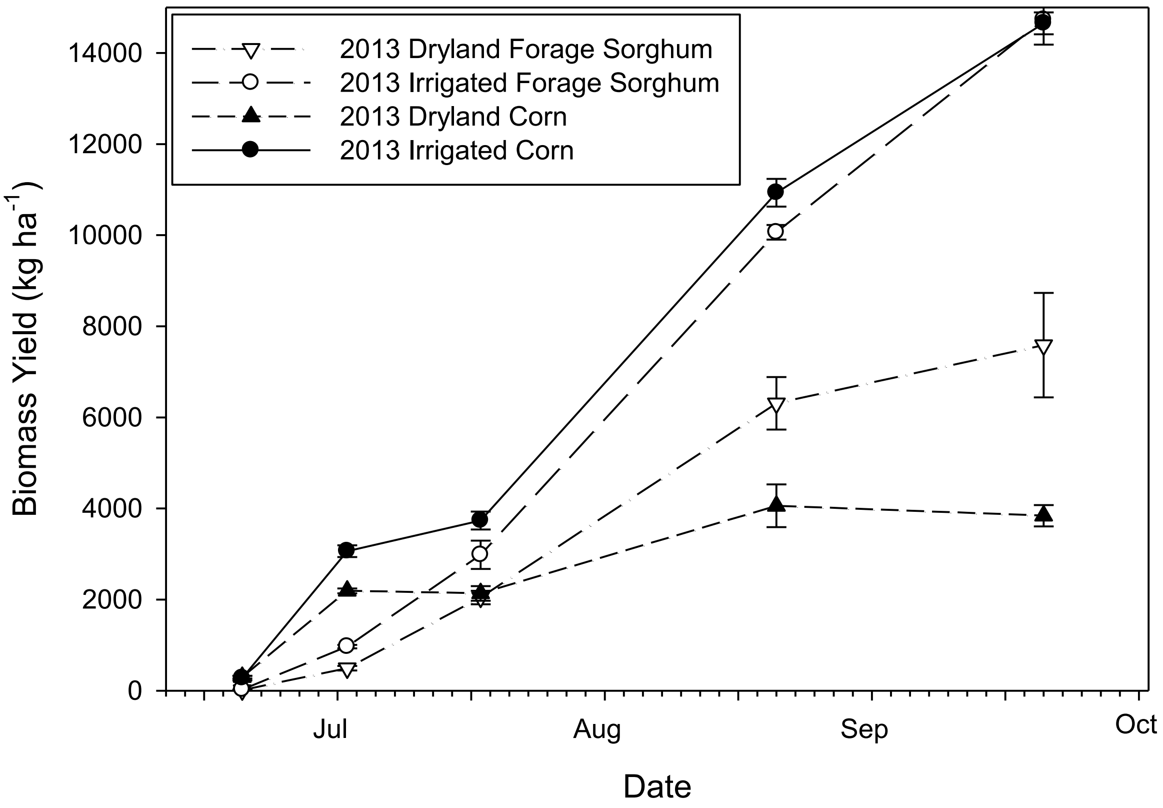


Figure 3-7. Biomass accumulation over growing season, Hoxie, Kansas 2013.

Table 3-6. Available water content Hoxie, Kansas 2011.

Date	Depth	Irrigated forage sorghum	SE	Irrigated corn	SE	Dryland forage sorghum	SE	Dryland corn	SE
	cm	Available water content cm^3 cm^{-3}							
4/7/2011	30	0.223	0.0079	0.230	0.0093	0.219	0.0106	0.105	0.0086
	61	0.220	0.0133	0.249	0.0038	0.240	0.0130	0.233	0.0049
	91	0.176	0.0046	0.207	0.0108	0.202	0.0061	0.199	0.0259
	122	0.141	0.0245	0.174	0.0123	0.088	0.0311	0.115	0.0394
	152	0.118	0.0231	0.144	0.0151	0.031	0.014	0.068	0.0337
	183	0.092	0.0238	0.117	0.0164	0.117	0.0164	0.028	0.0124
	213	0.083	0.0211	0.089	0.0103	0.017	0.0043	0.026	0.0076
	244	0.100	0.0151	0.084	0.0079	0.034	0.0056	0.048	0.0060
16/7/2011	30	0.241	0.0042	0.239	0.0040	0.217	0.0083	0.108	0.0045
	61	0.228	0.0177	0.223	0.0116	0.250	0.0088	0.214	0.0042
	91	0.209	0.0111	0.214	0.0061	0.207	0.0114	0.213	0.0182
	122	0.181	0.0118	0.198	0.0066	0.112	0.0262	0.137	0.0299
	152	0.152	0.0152	0.185	0.0099	0.053	0.0198	0.085	0.0325
	183	0.112	0.0147	0.146	0.0017	0.024	0.0064	0.051	0.0148
	213	0.090	0.0205	0.110	0.0114	0.034	0.0089	0.043	0.0031
	244	0.096	0.0113	0.110	0.0222	0.042	0.0051	0.062	0.0055
4/8/2011	30	0.222	0.0083	0.227	0.0138	0.213	0.0111	0.222	0.0152
	61	0.210	0.0184	0.209	0.0033	0.189	0.0144	0.193	0.0130
	91	0.183	0.0139	0.155	0.0112	0.163	0.0143	0.155	0.112
	122	0.171	0.0146	0.190	0.0077	0.097	0.0221	0.118	0.0170
	152	0.162	0.0202	0.181	0.0113	0.063	0.0225	0.085	0.0236
	183	0.127	0.0066	0.177	0.0107	0.032	0.0149	0.063	0.0195
	213	0.103	0.0183	0.136	0.0075	0.037	0.0125	0.054	0.0119
	244	0.107	0.0180	0.114	0.0054	0.048	0.0118	0.064	0.0057

Table 3-6 Continued

4/9/2011	30	0.227	0.0121	0.224	0.0011	0.095	0.0032	0.046	0.0142
	61	0.215	0.0099	0.237	0.0078	0.143	0.0040	0.154	0.0078
	91	0.187	0.0110	0.176	0.0148	0.102	0.0045	0.142	0.0125
	122	0.168	0.01587	0.145	0.0118	0.040	0.0206	0.060	0.0052
	152	0.133	0.0018	0.143	0.0098	0.015	0.0056	0.042	0.0064
	183	0.116	0.0038	0.147	0.0103	0.002	0.0012	0.033	0.0100
	213	0.129	0.0114	0.140	0.0146	0.008	0.0053	0.036	0.0076
	244	0.132	0.0099	0.147	0.0102	0.030	0.0041	0.060	0.0065
16/10/2011	30	0.215	0.0058	0.204	0.0043	0.237	0.0020	0.225	0.0109
	61	0.196	0.0167	0.239	0.0070	0.181	0.0226	0.217	0.0079
	91	0.161	0.0147	0.183	0.0116	0.107	0.0190	0.208	0.0085
	122	0.134	0.0172	0.156	0.0107	0.037	0.0212	0.099	0.0235
	152	0.123	0.0176	0.145	0.0114	0.029	0.0256	0.030	0.0052
	183	0.112	0.0113	0.146	0.0142	0.020	0.0199	0.016	0.0071
	213	0.099	0.0151	0.128	0.0148	0.014	0.0139	0.024	0.0047
	244	0.111	0.0123	0.130	0.0081	0.018	0.0179	0.049	0.0039

Table 3-7. Available soil water by depth Hoxie, Kansas 2012.

Date	Depth	Irrigated forage sorghum	SE	Irrigated corn	SE	Dryland sorghum	SE	Dryland corn	SE
	cm	Available water content cm^3 cm^{-3}							
11/6/2012	30	0.210	0.0163	0.197	0.0147	0.180	0.0178	0.146	0.0228
	61	0.187	0.0043	0.205	0.0138	0.229	0.0152	0.230	0.0158
	91	0.137	0.0148	0.180	0.0290	0.229	0.0163	0.232	0.0104
	122	0.131	0.0167	0.144	0.0249	0.118	0.0287	0.144	0.0106
	152	0.121	0.0101	0.144	0.0221	0.066	0.0155	0.076	0.0103
	183	0.108	0.0120	0.136	0.0154	0.069	0.0062	0.070	0.0155
	213	0.107	0.0061	0.130	0.0060	0.063	0.0174	0.092	0.0182
	244	0.109	0.0071	0.123	0.0037	0.069	0.0198	0.093	0.0198
24/6/2012	30	0.247	0.0133	0.241	0.0071	0.226	0.0032	0.132	0.0171
	61	0.212	0.0137	0.211	0.0136	0.253	0.0052	0.208	0.0180
	91	0.154	0.0168	0.176	0.0173	0.257	0.0068	0.221	0.0103
	122	0.147	0.0185	0.188	0.0272	0.125	0.0302	0.149	0.0092
	152	0.136	0.0129	0.151	0.0183	0.075	0.0189	0.082	0.0116
	183	0.123	0.0115	0.148	0.0146	0.077	0.0076	0.072	0.0176
	213	0.103	0.0028	0.122	0.0085	0.068	0.0199	0.091	0.0195
	244	0.137	0.0241	0.145	0.0091	0.079	0.0209	0.088	0.0201
14/7/2012	30	0.226	0.0122	0.243	0.0050	0.204	0.0131	0.163	0.0171
	61	0.188	0.0077	0.206	0.0056	0.210	0.0168	0.173	0.0197
	91	0.144	0.0161	0.152	0.0176	0.225	0.0104	0.176	0.0111
	122	0.142	0.0182	0.159	0.0184	0.203	0.0178	0.127	0.0102
	152	0.136	0.0142	0.151	0.0258	0.150	0.0193	0.082	0.0089
	183	0.125	0.0172	0.141	0.0138	0.100	0.0060	0.069	0.0184
	213	0.106	0.0025	0.144	0.0100	0.091	0.0111	0.109	0.0237
	244	0.119	0.0061	0.142	0.0036	0.089	0.0150	0.100	0.0226

Table 3-7 Continued

28/7/2012	30	0.174	0.0032	0.159	0.0090	0.061	0.0038	0.065	0.0124
	61	0.117	0.0040	0.139	0.0132	0.129	0.0051	0.139	0.0156
	91	0.076	0.0057	0.102	0.0207	0.129	0.0015	0.144	0.0102
	122	0.096	0.0037	0.112	0.0105	0.116	0.0076	0.084	0.0124
	152	0.100	0.0046	0.110	0.0110	0.107	0.0027	0.056	0.0098
	183	0.099	0.0056	0.105	0.0078	0.089	0.0025	0.057	0.0179
	213	0.091	0.0030	0.104	0.0039	0.091	0.0060	0.073	0.0149
	244	0.111	0.0019	0.112	0.0079	0085	0.0181	0.077	0.0184
18/9/2012	30	0.118	0.0223	0.150	0.0061	0.056	0.0011	0.103	0.00084
	61	0.066	0.0094	0.092	0.0108	0.095	0.0026	0.139	0.0128
	91	0.010	0.0070	0.043	0.0253	0.112	0.0117	0.126	0.0068
	122	0.021	0.0080	0.059	0.0286	0.079	0.0249	0.057	0.0037
	152	0.024	0.0115	0.081	0.0324	0.032	0.0078	0.042	0.0080
	183	0.040	0.0229	0.079	0.0100	0.0	0.0	0.058	0.0048
	213	0.041	0.0146	0.084	0.0042	0.0	0.0	0.067	0.0030
	244	0.076	0.0109	0.092	0.0097	0.008	0.0073	0.078	0.0064

Table 3-8. Available soil water by depth Hoxie, Kansas 2013.

Date	Depth	Irrigated Forage sorghum	SE	Irrigated corn	SE	Dryland sorghum	SE	Dryland corn	SE
	cm			Available water content cm^3 cm^{-3}					
28/6/2013	30	0.163	0.0027	0.086	0.0058	0.149	0.0103	0.146	0.0228
	61	0.162	0.0163	0.166	0.0232	0.192	0.0208	0.230	0.0158
	91	0.050	0.0147	0.064	0.0193	0.148	0.0152	0.232	0.0104
	122	0.013	0.0088	0.034	0.0131	0.091	0.0071	0.144	0.0106
	152	0.009	0.0045	0.018	0.0014	0.079	0.0050	0.076	0.0103
	183	0.010	0.0056	0.016	0.0054	0.061	0.0043	0.070	0.0155
	213	0.027	0.0040	0.029	0.0078	0.075	0.0055	0.092	0.0182
	244	0.059	0.0033	0.062	0.0069	0.111	0.0074	0.093	0.0198
9/7/2013	30	0.159	0.0036	0.118	0.0135	0.100	0.0093	0.055	0.0032
	61	0.209	0.0050	0.144	0.0126	0.187	0.0195	0.109	0.0198
	91	0.068	0.0137	0.054	0.0118	0.146	0.0149	0.136	0.0027
	122	0.019	0.0116	0.017	0.0044	0.095	0.0082	0.085	0.0248
	152	0.010	0.0045	0.018	0.0041	0.082	0.0052	0.060	0.0179
	183	0.012	0.0055	0.019	0.0053	0.064	0.0047	0.056	0.0109
	213	0.027	0.0049	0.029	0.0084	0.077	0.0042	0.081	0.0056
	244	0.059	0.0039	0.066	0.0071	0.107	0.0083	0.091	0.0042
23/7/2013	30	0.126	0.0105	0.105	0.0189	0.047	0.0115	0.038	0.0053
	61	0.179	0.0096	0.103	0.0091	0.120	0.0220	0.079	0.0110
	91	0.066	0.0128	0.037	0.0069	0.147	0.0146	0.117	0.0281
	122	0.017	0.0109	0.018	0.0035	0.099	0.0073	0.077	0.0277
	152	0.012	0.0059	0.018	0.0047	0.084	0.0044	0.060	0.0173
	183	0.017	0.0070	0.023	0.0041	0.066	0.0049	0.058	0.0081
	213	0.033	0.0057	0.030	0.0075	0.076	0.0059	0.084	0.0042
	244	0.064	0.0046	0.069	0.0058	0.112	0.0075	0.091	0.0034

Table 3.8 Continued

23/8/2013	30	0.133	0.0102	0.149	0.0203	0.068	0.0115	0.067	0.0099
	61	0.186	0.0048	0.162	0.0090	0.136	0.0247	0.134	0.0248
	91	0.084	0.0010	0.049	0.0139	0.137	0.0136	0.120	0.0283
	122	0.018	0.0141	0.014	0.0051	0.086	0.0069	0.070	0.0281
	152	0.012	0.0039	0.015	0.0036	0.071	0.0028	0.055	0.0177
	183	0.014	0.0051	0.022	0.0047	0.062	0.0043	0.053	0.0123
	213	0.029	0.0064	0.029	0.0085	0.073	0.0050	0.077	0.0055
	244	0.058	0.0041	0.063	0.0042	0.106	0.0071	0.084	0.0030
20/9/2013	30	0.189	0.0023	0.230	0.0052	0.176	0.0028	0.214	0.0052
	61	0.164	0.0065	0.185	0.0084	0.130	0.0279	0.140	0.0246
	91	0.014	0.0079	0.036	0.0077	0.124	0.0092	0.109	0.0265
	122	0.007	0.0042	0.015	0.0044	0.067	0.0043	0.056	0.0195
	152	0.009	0.0036	0.018	0.0034	0.043	0.0064	0.041	0.0153
	183	0.011	0.0040	0.023	0.0055	0.040	0.0050	0.048	0.0118
	213	0.024	0.0054	0.031	0.0080	0.064	0.0076	0.077	0.0031
	244	0.060	0.0055	0.066	0.0060	0.109	0.0064	0.091	0.0042

Table 3-9. Available soil water in the 244 cm by date Hoxie, Kansas, 2011.

	4/7/2011		16/7/2011		4/8/2011		4/9/2011		16/10/2011	
	Available soil water	SE	Available soil water	SE	Available soil water	SE	Available soil water	SE	Available soil water	SE
	mm in 244 cm soil profile									
Irrigated forage sorghum	348	28	383	12	370	15	373	3	344	23
Irrigated corn	378	14	401	2	390	4	371	4	377	7
Dryland forage sorghum	256	19	285	12	256	25	133	9	195	40
Dryland corn	250	33	277	27	289	31	174	18	264	13

Table 3-10. Available soil water in the 244 cm profile by date Hoxie, Kansas, 2012.

	11/6/2012		24/6/2012		14/7/2012		28/7/2012		18/09/2012	
	Available soil water	SE	Available soil water	SE	Available soil water	SE	Available soil water	SE	Available soil water	SE
	mm in 244 cm soil profile									
Irrigated forage sorghum	337	21	373	18	355	18	263	7	121	20
Irrigated corn	385	26	316	20	385	14	286	15	207	32
Dryland forage sorghum	311	18	339	17	379	8	246	8	116	9
Dryland corn	329	19	316	20	303	24	212	20	204	13

Table 3-11. Available soil water in the 244 cm profile by date Hoxie, Kansas, 2013.

	28/6/2013		9/7/2013		23/7/2013		23/8/2013		20/09/2013	
	Available soil water	SE	Available soil water	SE	Available soil water	SE	Available soil water	SE	Available soil water	SE
					mm in 244 cm soil profile					
Irrigated forage sorghum	150	16	171	13	156	13	163	11	145	10
Irrigated corn	144	13	142	17	123	16	153	15	184	10
Dryland forage sorghum	275	13	262	11	228	10	225	12	229	9
Dryland corn	208	13	204	16	184	20	201	24	236	20

Table 3-12. End of growing season water use for Hoxie, Kansas.

Year	Irrigated forage sorghum	SE	Irrigated corn	SE	Dryland forage sorghum	SE	Dryland corn	SE
				mm				
2011	663	34	666	15	365	32	289	40
2012	675	22	598	22	295	10	234	14
2013	532	15	487	16	207	8	134	12

Table 3-13. End of season biomass water use efficiency (WUE_b) Hoxie, Kansas 2011, 2012 and 2013.

Year	Irrigated forage sorghum	SE	Irrigated corn	SE	Dryland forage sorghum	SE	Dryland corn	SE
				kg ha^{-1} mm^{-1}				
2011	27.30	0.5218	23.29	0.5100	23.16	2.326	22.57	4.3670
2012	27.96	2.750	11.15	1.077	23.15	1.444	11.33	1.624
2013	27.82	1.700	30.14	1.051	36.46	5.390	29.20	2.892

Table 3-14. Grain water use efficiency (WUE_g) for irrigated corn and dryland corn, Hoxie, Kansas.

Year	Irrigated corn WUEg	SE	Dryland corn WUEg	SE
		$kg\ ha^{-1}\ mm^{-1}$		
2011	16.41	0.2687	15.86	2.9300
2012	7.23	0.6489	7.337	1.1040
2013	21.13	1.1480	7.230	1.3880

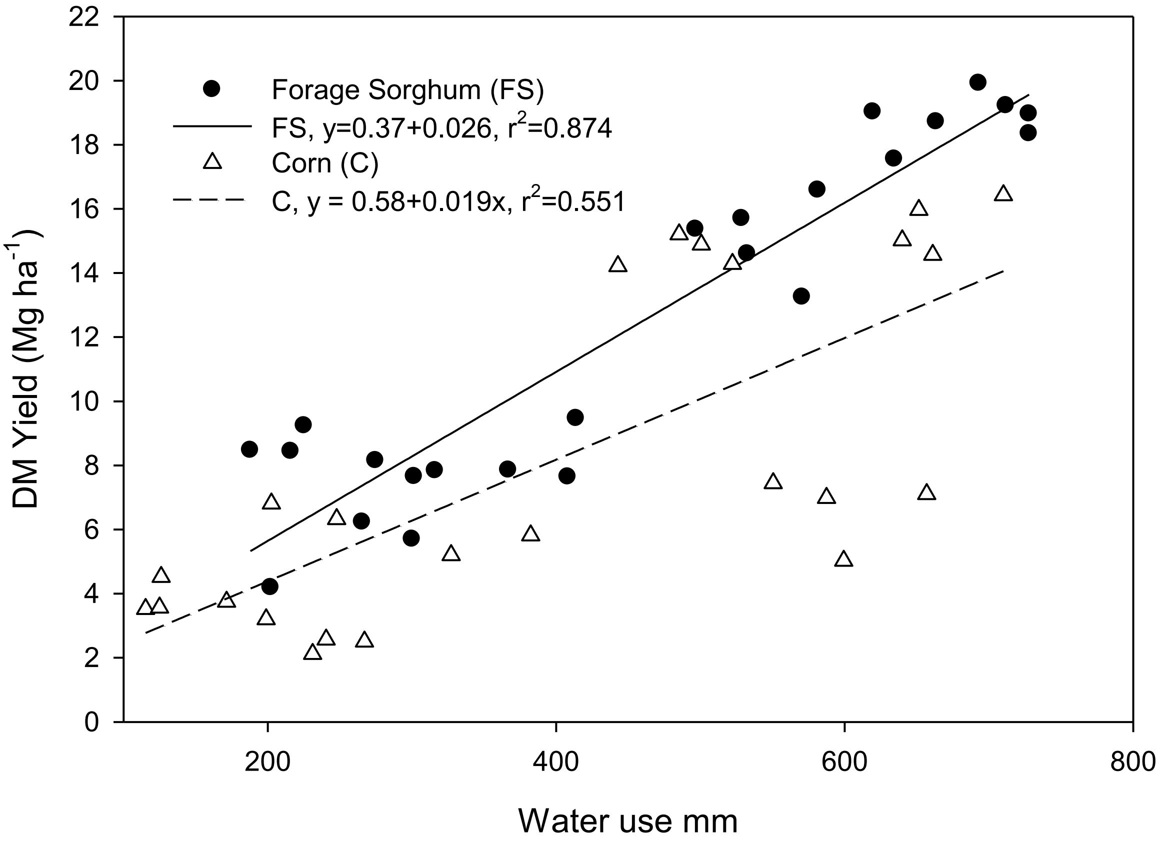


Figure 3-8 Dry matter (DM) biomass yield vs water use for Hoxie, Kansas 2011, 2012 and 2013.

Table 3-15. Fraction of intercepted photosynthetically active radiation (IPAR) for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn Hoxie, Kansas, 2011.

Date	Irrigated forage sorghum	SE	Irrigated corn	SE	Dryland forage sorghum	SE	Dryland corn	SE
				Fraction of PAR intercepted				
4/7/2011	0.030	0.001	0.118	0.008	0.031	0.009	0.132	0.026
16/7/2011	0.558	0.049	0.654	0.075	0.601	0.072	0.770	0.020
4/8/2011	0.993	0.003	0.935	0.009	0.984	0.005	0.966	0.006
4/9/2011	0.993	0.006	0.895	0.012	0.973	0.006	0.783	0.016
16/10/2011	0.843	0.009	0.517	0.028	0.818	0.008	0.434	0.011

Table 3-16 Fraction of intercepted photosynthetically active radiation (IPAR) for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn Hoxie, Kansas, 2012.

Date	Irrigated forage sorghum	SE	Irrigated corn	SE	Dryland forage sorghum	SE	Dryland corn	SE
				Fraction of PAR intercepted				
11/6/2012	0.022	0.004	0.283	0.014	0.011	0.005	0.194	0.025
24/6/2012	0.389	0.012	0.607	0.006	0.307	0.046	0.507	0.075
14/7/2012	0.994	0.017	0.785	0.119	0.897	0.028	0.453	0.013
28/7/2012	0.875	0.031	0.843	0.026	0.867	0.020	0.740	0.019
18/9/2012	0.983	0.003	0.803	0.013	0.983	0.003	0.696	0.013

Table 3-17. Fraction of intercepted photosynthetically active radiation (IPAR) for irrigated forage sorghum, irrigated corn, dryland forage sorghum and dryland corn Hoxie, Kansas, 2013.

Date	Irrigated forage sorghum	SE	Irrigated corn	SE	Dryland forage sorghum	SE	Dryland corn	SE
				Fraction of PAR intercepted				
28/6/2012	0.071	0.019	0.426	0.012	0.067	0.005	0.341	0.050
9/7/2012	0.253	0.040	0.324	0.048	0.466	0.025	0.277	0.041
23/7/2012	0.987	0.001	0.845	0.008	0.556	0.011	0.729	0.004
23/8/2012	0.992	0.005	0.886	0.009	0.992	0.003	0.836	0.001
20/9/2012	0.984	0.002	0.742	0.002	0.985	0.003	0.632	0.003

Table 3-18. Nutritional values Hoxie, Kansas 2012.

	2012									
	Fraction of crude protein	SE	Fraction of ADF	SE	Fraction of NDF	SE	Prussic acid ppm	SE	Nitrate mg kg^{-1} NO3-N	SE
Irrigated forage sorghum	7.25	0.119	37.86	1.033	59.83	0.576	514.50	10.170	1530.00	66.207
Dryland forage sorghum	11.55	0.155	27.65	0.247	53.23	0.440	474.25	52.889	1762.50	257.370
Irrigated corn	7.43	0.125	49.05	0.126	77.38	0.407	20.25	3.276	3385.00	108.666
Dryland corn	10.23	0.419	29.80	0.925	55.78	1.209	40.50	1.041	534.00	67.305

Table 3-19. Nutritional values Hoxie, Kansas 2013.

	2013									
	Fraction of crude protein	SE	Fraction of ADF	SE	Fraction of NDF	SE	Prussic acid mg/kg	SE	Nitrate mg kg^{-1} NO3-N	SE
Irrigated forage sorghum	10.40	0.540	41.20	0.596	61.43	0.837	184.75	35.472	3067.50	65.495
Dryland forage sorghum	12.45	0.384	38.20	0.615	59.75	0.144	192.75	49.570	4675.00	367.070
Irrigated corn	9.88	0.193	43.15	2.153	71.63	2.823	25.25	2.175	4312.50	541.346
Dryland corn	10.23	0.423	37.43	2.533	62.58	3.657	28.50	2.598	3130.00	575.354

References

Al-Kasi, M.M., A.F. Berrada, and M.W. Stack. 1997. Evaluation of irrigation scheduling program and spring wheat yield response in southwestern Colorado. Agric. Water Manage. 34:137-148.

Ankom. 2006. Ankom Technology Method 5. Acid detergent fiber in feeds. Filter Bag Technique. Ankom Technology. Macedon, New York. Modification of method AOAC Official Method 973.18. Fiber (acid detergent) and Lignin (H_2SO_4) in animal feed. Official methods analysis of AOAC International. 19th ed. Dr. George Latimer, Jr (ed). Gaithersburg, Maryland.

Ankom 2006. Ankom Technology Method 6. Neutral detergent fiber in feeds. Filter Bag Technique. Ankom Technology. Macedon, New York. Modification of method AOAC Official Method 2002.04. Amylase-treated neutral detergent fiber in feeds. Using refluxing in beakers or crucibles. Official Methods of Analysis of AOAC International. 19th ed. Dr. George W. Latimer, Jr (ed). Gaithersburg Mayrland.

AOAC International. 2012. AOAC Official Method 990.03. Protein (crude) in animal feed. Combustion method. Official Methods of Analysis of AOAC International. 19th ed. Dr. George W. Latimer, Jr (ed). Gaithersburg, Maryland.

Arkin, G.F., W. D. Rosenthal, and W. R. Jordan. 1983. A sorghum leaf area model. ASAE Tech Paper 83-2098. Am. Soc. Agric. Eng., St. Joseph, Mich.

Aydin, G., R.J. Grant, and J. O'Rear. 1999. Brown midrib sorghum in diets for lactating dairy cows. J. Dairy Sci. 82:2127-2135.

Bean, B.W., R. L. Baumhardt, F. T. McCollum III, and K.C. McCuistion. 2013. Comparison of sorghum classes for grain and forage yield and forage nutritive value. Field Crops Res. 142:20-26.

Boote, K.J., and R.S. Loomis. 1991. The prediction of canopy photosynthesis. In: Boote, K.J., R.S. Loomis (Eds.), Modeling Photosynthesis-From Biochemistry to Canopy. CSSA Special Publication Number 19. Crop Science Society of America, Inc., American Society of Agronomy, Inc., Madison, Wisconsin, pp.109-140.

Cataldo, D.A., M. Haroon, L.E. Schrader, and V.L. Young, 1975. Rapid colorimetric determination of nitrate in plant tissue by nitration of salicylic acid. Comm. Soil. Sci. and Plant Ana. 6:71-80.

Condon, A.G., R.A. Richards., G.J. Rebetzke, and G.D. Farquhar. 2004. Breeding for high water use efficiency. J. of Exp. Bot. 55:2447-2460.

Crasta, O.R., W.J. Cox, and J.H. Cherney. 1997. Factors affecting maize forage quality development in the northeastern USA. Agron. J. 89:251-256.

Cummings, D.G. 1981. Yield and quality changes with maturity of silage-type sorghum fodder. Agron. J. 73:988-990.

Cox, W.J. J.H. Cherney, D.J.R. Cherney, and W.D. Pardee. 1994. Forage quality and harvest index of corn hybrids under different growing conditions. Agron. J. 86:277-282.

Dahlberg, J. 2000 Classification and characterization of sorghum. In: Smith, C.W., Frederiksen, R.A. (Eds.), Sorghum: Origin, History, Technology, and Production. John Wiley & Sons, Inc., New York, NY, pp. 99-130.

Denmead, O.T., and R.H. Shaw. 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. 52:272-274.

Dennehy, K.F. 2000. High Plains regional ground water study USGS Fact Sheet FS-091-00. U.S. Geol. Survey, Lincoln, NE.

Egekeze, J.O. and F. W. Oehme. 1980. Cyanides and their toxicity: A literature review. The Vetern. Quart. 2:104-114

Evans, L. T. 1993. Crop Evolution, Adaptation and Yield. Cambridge University Press, Cambridge, UK.

Evett, S.R., and J.L. Steiner. 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. Soil Sci. Soc. Am. J. 59:961-968.

Frank, B. J., A. J. Schlegel, L. R. Stone, and M.B. Kirkham. 2013. Grain Yield and Plant Characteristics of Corn Hybrids in the Great Plains.

Gillingham, J.T., M.M. Shirer, and N.R. Page. 1969. Evaulation of the Orion Cyanide Electrode for estimating the cyanide content of forage samples. Agron. J. 61:717-718.

Hao, B., Q. Xue, B.W. Bean, W.L. Rooney, and J.D. Becker. 2014. Biomass production, water and nitrogen use efficiency in photoperiod-sensitive sorghum in the Texas High Plains. Biomass Bioenerg. 62:108-116.

Harms, C.L., and B. B. Tucker. Influence of nitrogen fertilization and other factors on yield, prussic acid, nitrate and total nitrogen concentrations of sudangrass cultivars. Agron. J. 65:22-26.

Hattendorf, M. J., M. S. Redelfs, B. Amos, L.R. Stone, and R. E. Gwin Jr. 1998. Comparitive water use characteristics of six row crops. Agron. J. 80:80-85.

Howell, T. A., J.L. Steiner, A.D. Schneider, S.R. Evett, and J.A. Tolk. 1997. Seasonal and maximum daily evapotranspiration of irrigated wheat, sorghum, and corn – Southern High Plains. Trans. Am Soc. Agric. Eng. 40:623-634.

Howell, T., A. Yazar, A. D. Schneider, and D. A. Dusek. 1995. Yield and water use efficiency of corn in response to LEPA irrigation. Trans. ASAE 38:1737-1747.

Howell, T.A., J.L. Steiner, A.D. Schneider, S.R. Evett, and J.A. Tolk. 1997. Seasonal and maximum daily evapotranspiration of irrigated wheat, sorghum, and corn- Southern High Plains. Trans. Am. Soc. Agric. Eng. 40:623-634.

Howell, T.A., S.R. Evett, J.A. Tolk, K.S. Copeland, P.D. Colaizzi, and P.H. Gowda. 2008. Evapotranspiration of corn and forage sorghum for silage. In: Soil and water Management Research News. USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, USA. Wetting Front Newsletter 10 (June (1)).

Johnson, R.R., and K.E. McClure. 1968. Corn plant maturity: IV. Effects on digestibility of corn silage in sheep. J. Anim. Sci. 27:535-539.

Klocke, N. L., L. R. Stone, G. A. Clark, T. J. Dumler, and S. Briggeman. 2006. Water allocation model for limited irrigation Applied Eng. Agric. 22:381-389.

Klute, A., and C. Dirksen. 1986. Water retention: Laboratory methods. P. 635-662. In A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. SSSA Book Series no. 5. SSSA and ASA, Madison, WI.

KWO. 2011. 2011 Kansas water use reporting. Topeka, Kans.: Kansas Water Office.

Lamm, F.R., L. R. Stone and D. M. O'Brien. 2007. Crop production and economics in Northwest Kansas as related to irrigation capacity. Applied Eng. in Agric. 23:737-745.

Lauer, J. G., J. G. Coors, and P. J. Flannery. 2001. Forage yield and quality of corn cultivars developed in different eras. Crop Sci. 41:1449-1455.

Marsalis, M. A., and B. Bean. 2010. Western forage production guide. Lubbock, TX, USA: United Sorghum Checkoff Program, Available from http://amarillo.tamu.edu/files/2010/11/WesternForageGuide_FINAL.pdf

Marsalis, M. A., S.V. Angadi, and F.E. Contreras-Govea. 2010. Dry matter yield and nutritive value of corn, forage sorghum, and BMR forage sorghum at different plant populations and nitrogen rates. Field Crops Res. 116:52-527.

Marsalis, M.A., S.V. Angadi, F.E. Contreras-Govea. 2010. Dry matter yield and nutritive value of corn, forage sorghum, and BMR forage sorghum at different plant populations and nitrogen rates. Field Crops Research. 116:52-57.

Martin, D. L., J. R. Gilley, and R. J. Supalla. 1989. Evaluation of irrigation planting decisions. Journal of Irrigation and Drainage Engineering. 115:58-77.

McCollum, T., K. McCuistion, and B. Bean. 2005. Brown midrib and photoperiod-sensitive forage sorghum. In: Proceedings of the 2005 plains nutrition council spring conference; Apr 14-15; San Antonio, TX. Amarillo, TX, USA; Texas A&M Univ. Ag. Res. and Ext. Center; pp. 36-46.

McCuistion, K.C., B.W. Bean, and F.T. McCollum III. 2009. Yield and water-use efficiency response to irrigation level of brown midrib, non-brown midrib and photoperiod-sensitive forage sorghum cultivars. Forage Grazinglands. doi:10.1094/FG-2010-0428-01-RS.

McCuistion, K.C., B.W. Bean, F.T. McCollum III. 2010. Nutritional composition response to yield differences in brown midrib, non-brown midrib, and photoperiod sensitive forage sorghum cultivars. Forage and Grazinglands doi:10.1094/FG-2010-0428-01-RS.

McGuire, V.L. 2004. Water-level changes in the High Plains Aquifer, predevelopment to 2002, 1980 to 2002, and 2001 to 2002. USGS Fact Sheet FS-2004-3026. U.S. Geological Survey, Denver, CO.

McMaster, G.S. and W.W. Wilhelm. 1997. Growing degree-days: one equation, two interpretations. Agric. and Forest Meteorology. 87:291-300.

Miron, J., E. Zuckerman, G. Adin, R. Soloman, E. Shoshani, M. Nikbachat, E. Yosef, A. Zenou, Z. Gershon Weinberg, Y. Chen, I. Halachmi, D. Ben-Ghedalia. 2007. Comparison of two forage sorghum varieties with corn and the effect of feeding their silages on eating behavior and lactation performance of dairy cows. Anim. Feed Sci. Technol. 139:23-29.

Muchow, R.C., T.R. Sinclair, and J.M. Bennett. 1990. Temperature and solar radiation effects on potential maize yield across locations. Agron. J. 82:338-343.

Norwood, C. A. (200) Water use and yield of limited-irrigated and dryland corn. Soil Sci. Soc. Am. J. 64:365-370.

NRC (National Research Council), 2001. Nutrient Requirements of Dairy Cattle: Seventh Revised Edition. National Academies Press, Washington, D.C.

NRC (National Research Council), 2001. Nutrient Requirements of Dairy Cattle: Seventh Revised Edition. National Academies Press, Washington, D.C.

Olson, T. 1971. Yield and water use by different populations of dryland corn, grains sorghum, and forage sorghum in the Western corn belt. Agron. J. 63:104-406.

Peterson, J.M., and D. J. Bernardo. 2003. High Plains Regional Aquifer Study revisited: A 20-year retrospective for Western Kansas. Great Plains Res. 13:179-197.

Pioneer Hi-bred International Inc. 35F48 Corn Seed. Pioneer, Johnson, IA. https://www.pioneer.com/home/site/us/

Rooney, W.L., J. Blumenthal, B. Bean, and J.E. Mullet. 2007. Designing sorghum as a dedicated bioenergy feedstock. Biofuels Bioprod. Bioref. 2:147-157.

Rosenthal, W.D., G.F. Arkin, P. J. Shouse, W. R. Jordan. 1987. Water deficit effects on transpiration and leaf growth. Agron J. 79:1019-1026.

Sanchez, A.C., P.K. Subudhi, D.T. Rosenow, and H.T. Nguyen. 2002. Mapping QTLs associated with drought resistance in sorghum (*Sorghum bicolor* L. Moench). J. Plant Mol. Biol. 48:713-726.

Schlegel, A.J., and J.L. Havlin. 1995. Corn response to long-term nitrogen and phosphorus fertilization. J. Prod. Agric. 8:181-185

Sinclair, T.R., C.B. Tanner, and J.M. Bennett. 1984. Water-use efficiency in crop production. BioScience. 34:36-40.

Sorghum Partners Inc., 2015. 1990 Hybrid Forage Sorghum, Technical Information. Sorghum Partners Inc. New Deal, TX, Available at http://www.chromatininc.com/products/25/1990

Sorghum Partners Inc., 2015. 1990 Hybrid Forage Sorghum, Technical Information. Sorghum Partners Inc. New Deal, TX, Available at http://www.chromatininc.com/products/25/1990

Steward, D. R., P.J. Bruss, X. Yang, S.A. Staggenborg, S. M. Welch, and M.D. Apley. 2013. Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110. Proc. Natl. Acad. Sci. USA. 110(137):3477-3486.

Stone, L.R., A.J. Schlegel, A.H. Khan, N.L. Klocke, and R.M. Aiken. 2006. Water Supply: Yield relationships developed for study of water management. J. Nat. Resour. Life. Sci. Educ. 35:161-173.

Stone, L.R., N.L. Klocke, A.J. Schlegel, F.R. Lamm, and D.J. Tomsicek. 2011. Equations for drainage component of the field water balance. App. Eng. Aric. 27:345-350.

Tolk, J.A., and T. A. Howell. 2003. Water use efficiencies of grain sorghum grown in three USA southern Great Plains soils. Agric. Water Manage. 59:97-111.

Turner, N.C. 1974. Stomatal behavior and water status of maize, sorghum and tobacco under field conditions. II. At low soil water potential. Plant Physiol. 55:360-365.

Weichenthal, B.A., D.D. Baltensperger, K.P. Vogel, S.D. Masterson, J.M. Blumenthal, and J.M. Krall. 2003. Annual forages for the Nebraska Panhandle. Tech. Bull. No. G1527. Univ. of Nebraska, Lincoln, NE.

Wheeler, J.L., C. Mulchay, J.J. Walcott and G.G. Rapp. 1990. Factors affecting the hydrogen cyanide potential of forage sorghum. Austral. J. Agric. Res. 41:1093-1100.

Yohannes, Y., T.E. Ochsner, and V. G. Kakani. 2015. Evapotranspiration partitioning and water use efficiency of switchgrass and biomass sorghum managed for biofuel. Agric. Wat. Man. 155:40-47.

Appendix A - Tribune Weather Data

Figure A-1 Maximum and minimum daily temperature for Tribune, Kansas 2011.

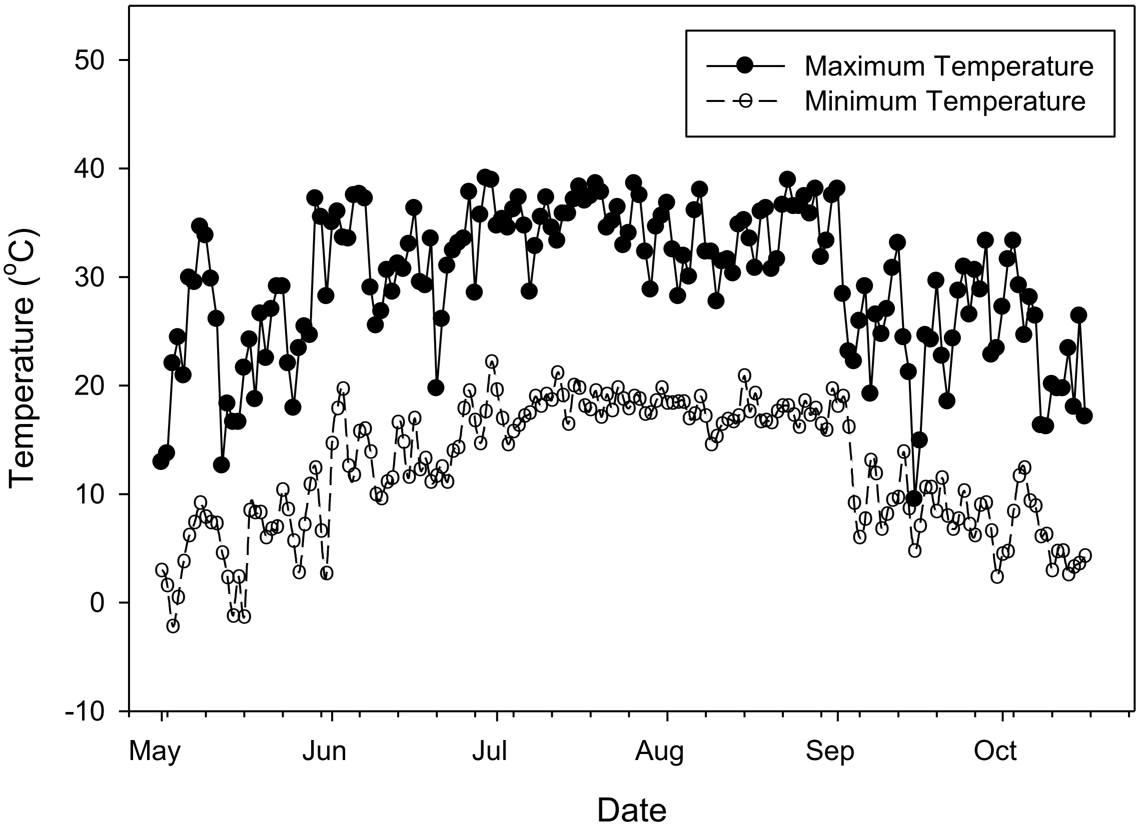


Figure A-2 Maximum and minimum daily temperatures for Tribune, Kansas 2012.

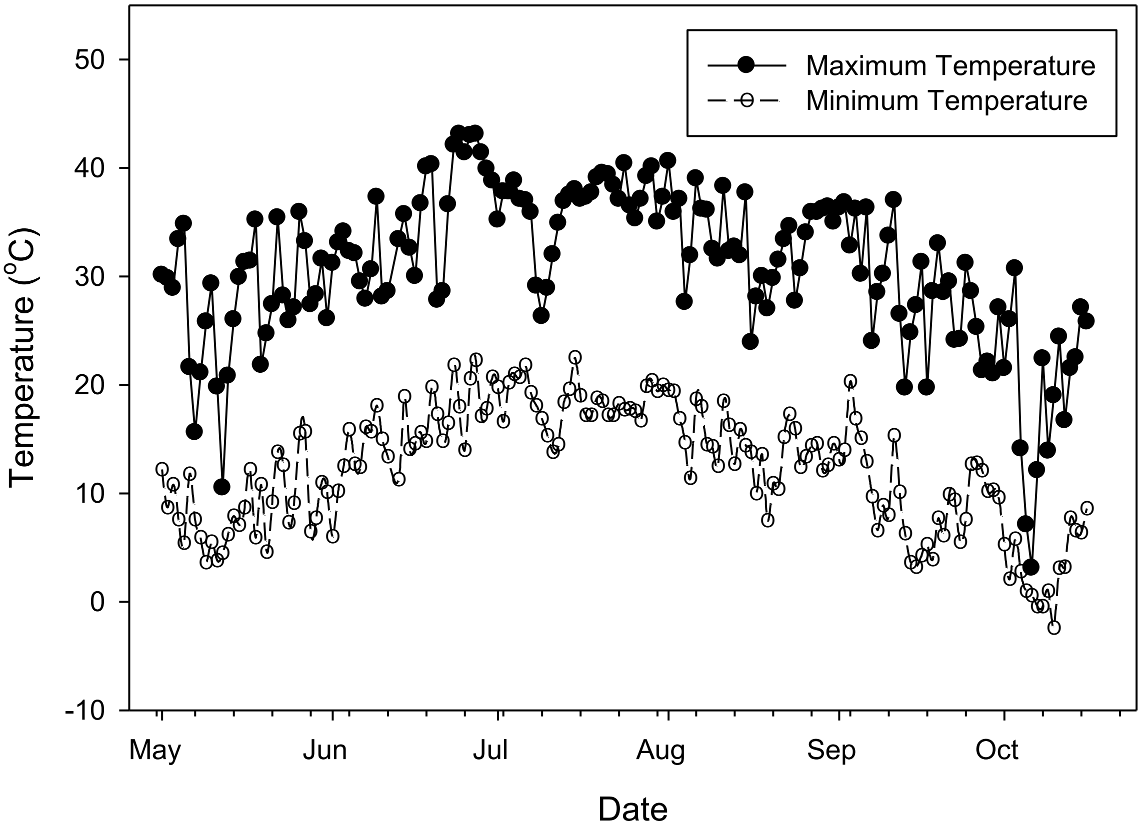
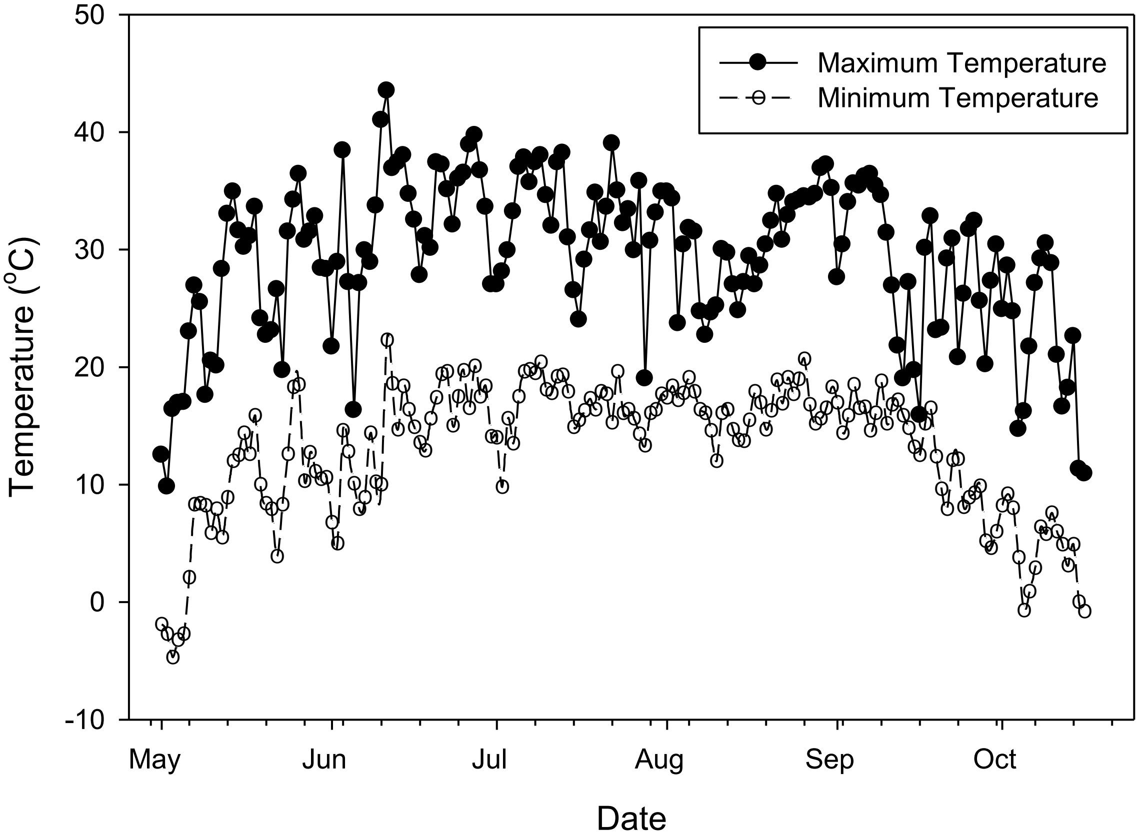


Figure A-3. Maximum and minimum daily temperatures for Tribune, Kansas 2013.



Appendix B - Hoxie Location

Figure B-1. Minimum and maximum daily temperatures for 2011, Hoxie, KS.

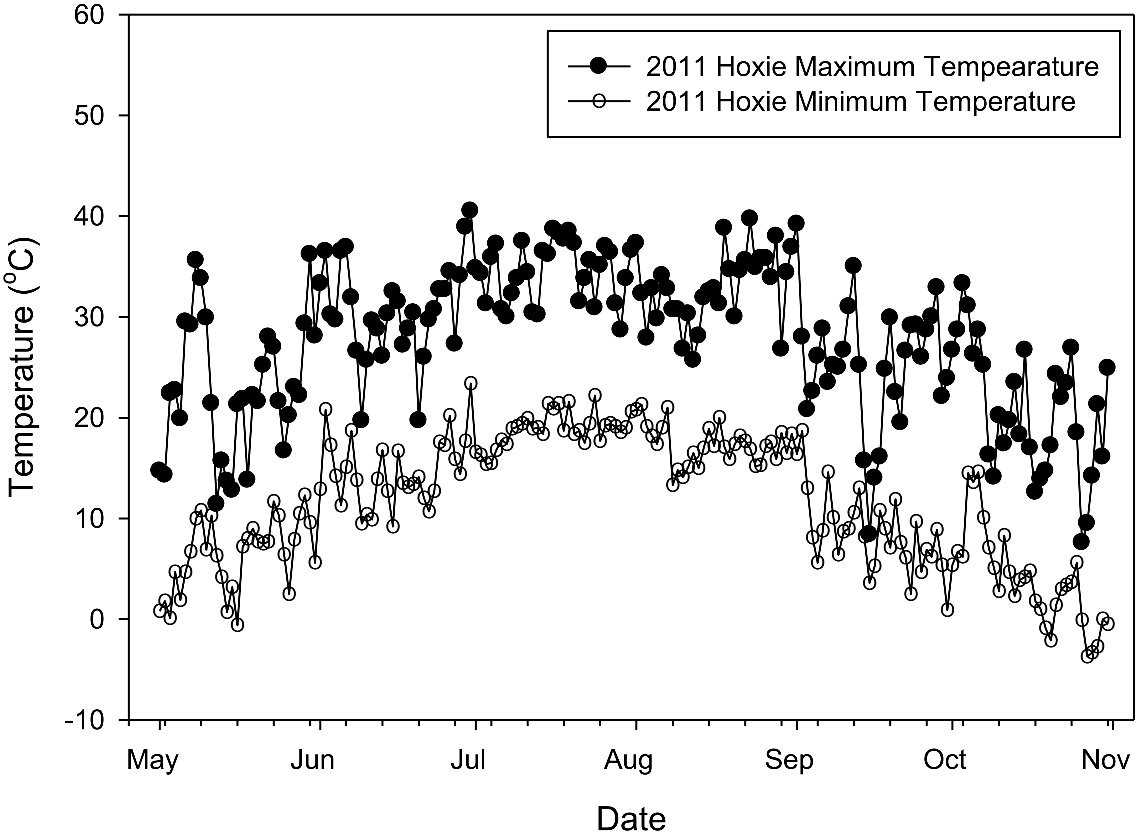


Figure B-2. Minimum and maximum daily temperatures for 2012, Hoxie, KS.

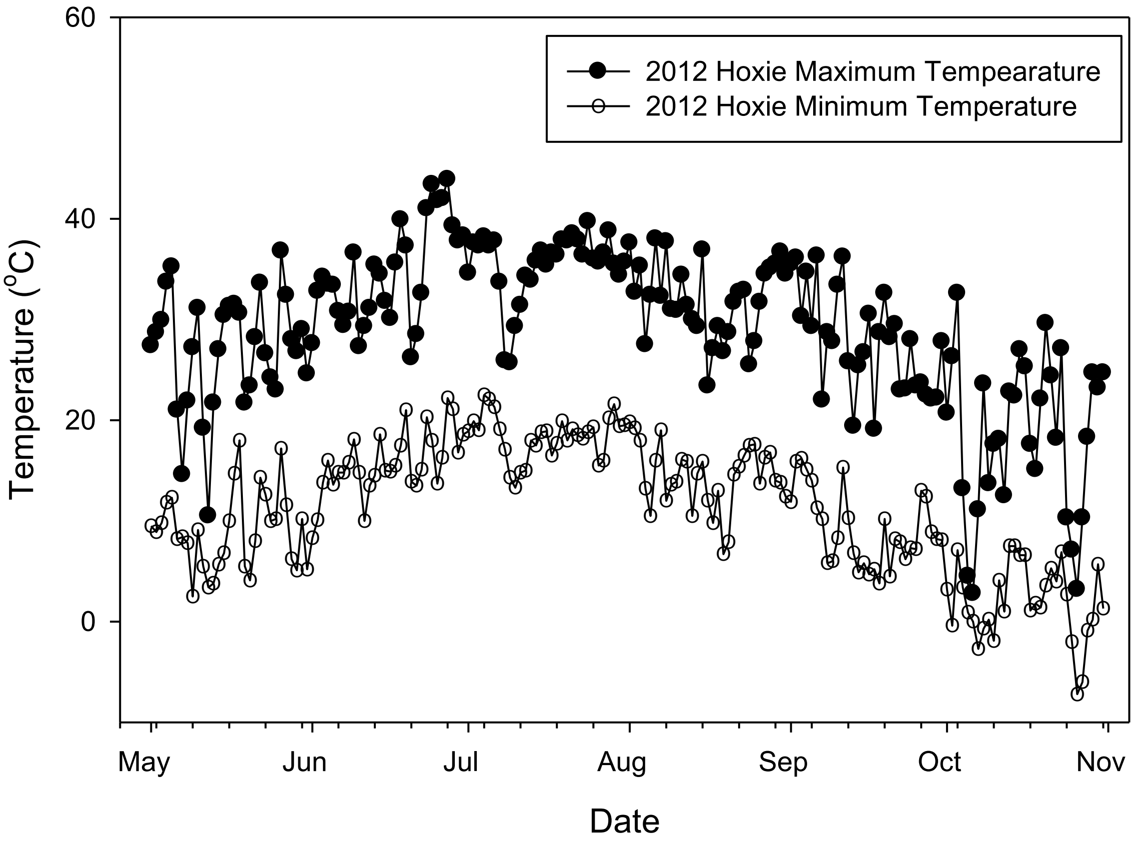


Figure B-3. Minimum and maximum daily temperatures for 2013, Hoxie, KS.

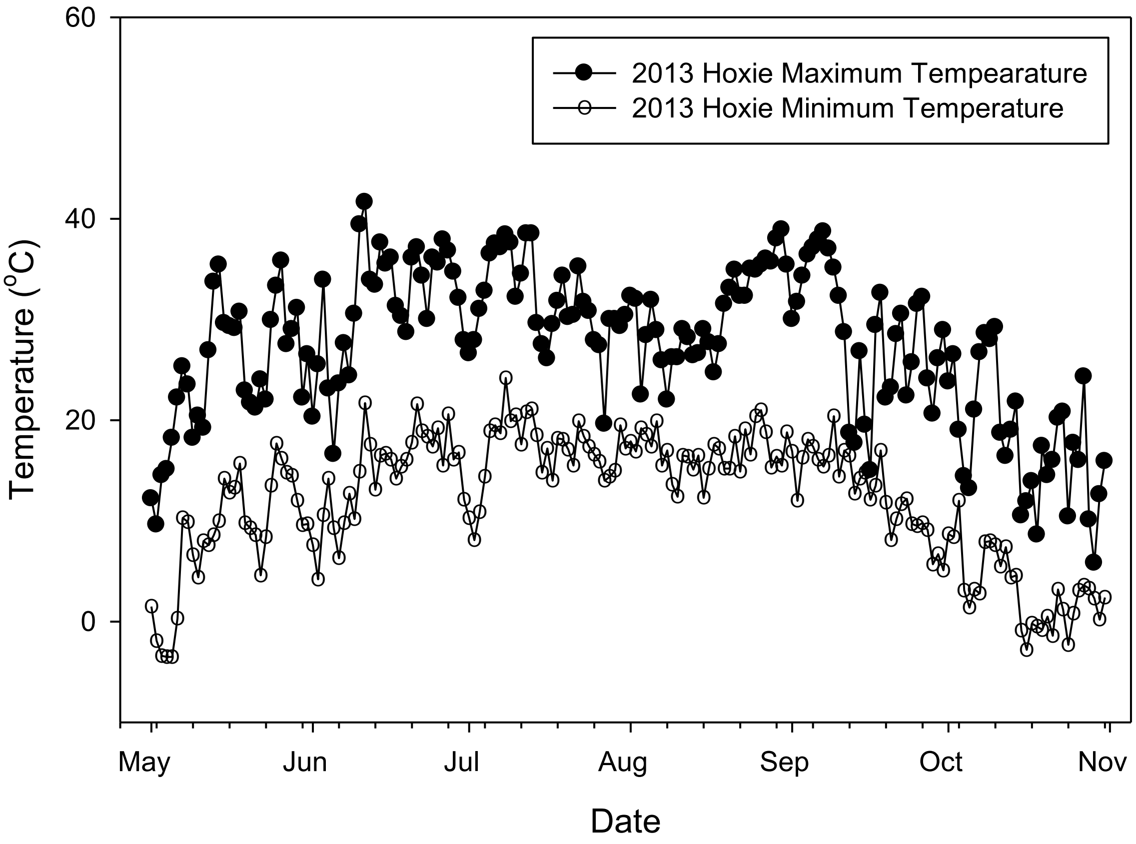


Figure B-4 Plot map for Hoxie, Kansas 2011 and 2012.

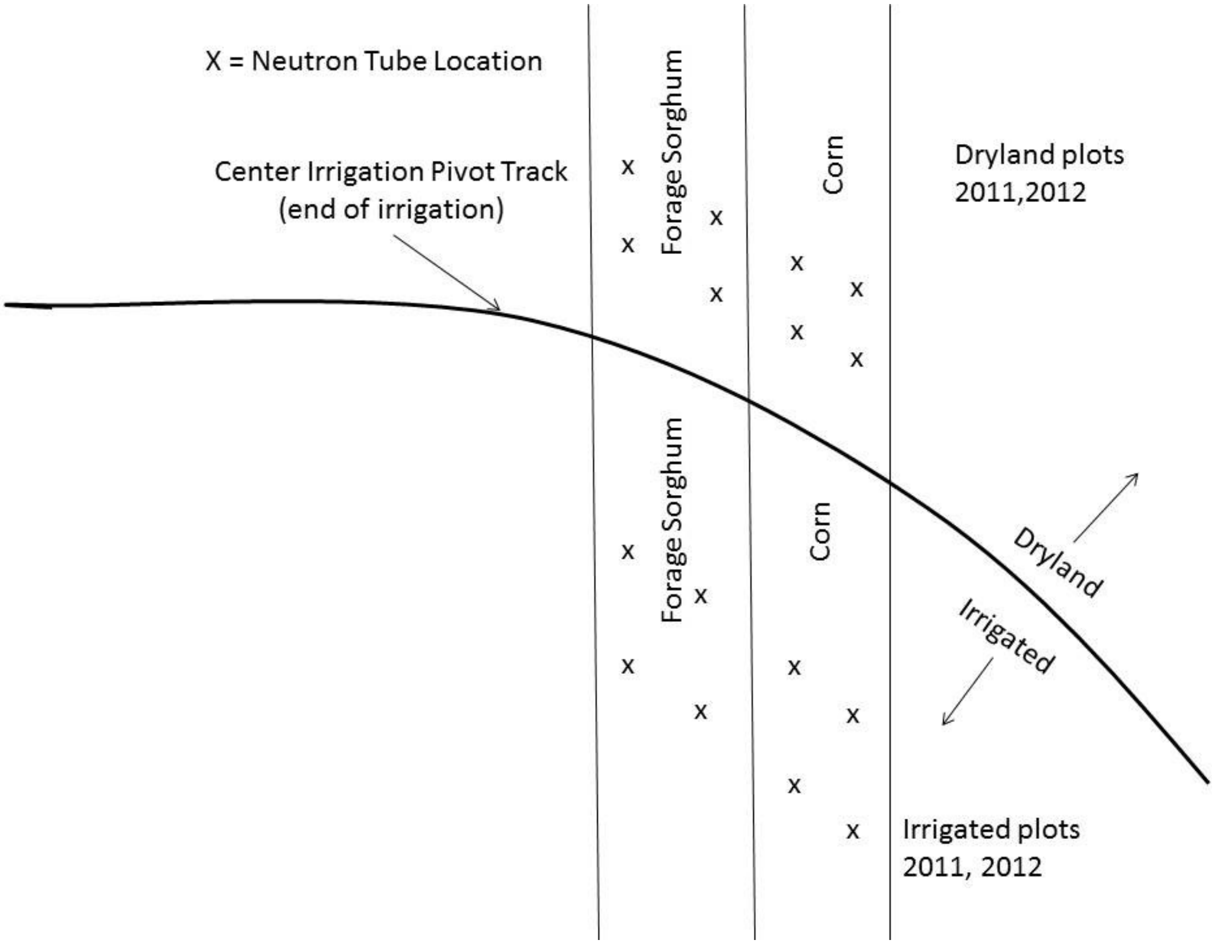


Figure B-5 Plot map for Hoxie 2013.

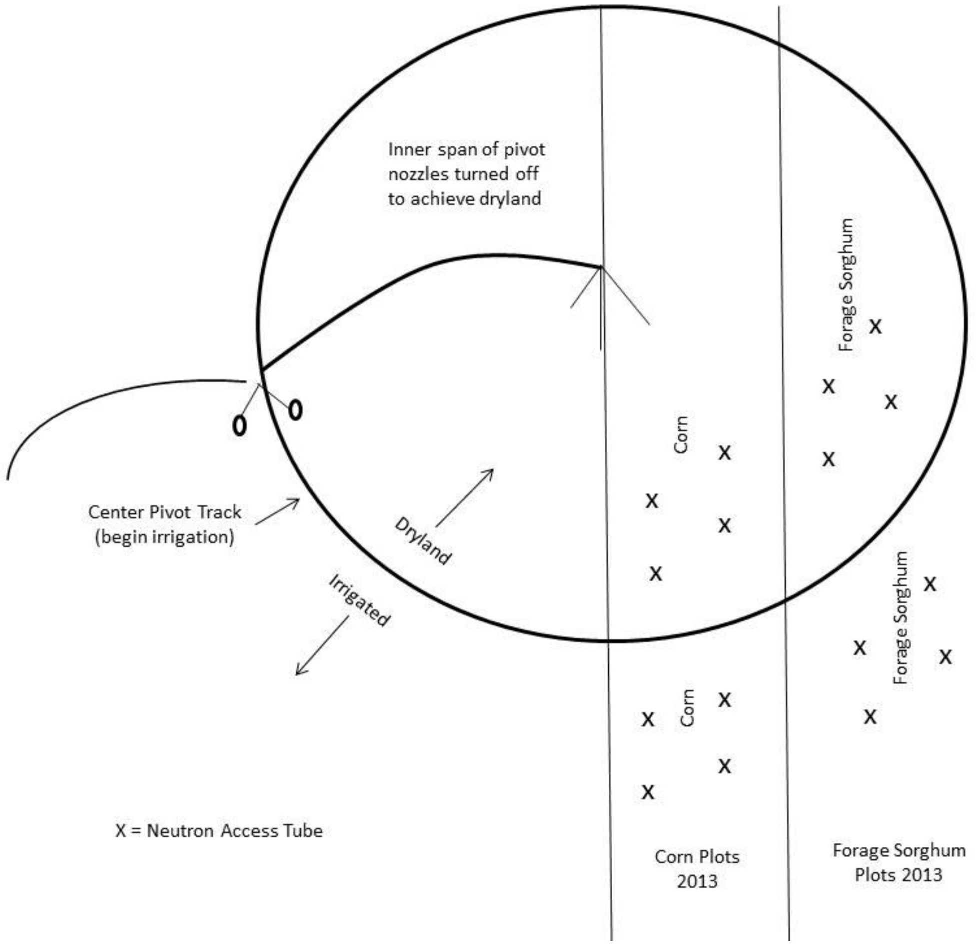


Table B-6 Measured bulk density values for Hoxie, Kansas 2011, 2012 and 2013.

Depth cm	Bulk density g cm^{-1}	SE
30	1.45	0.063
61	1.43	0.030
91	1.41	0.048
122	1.37	0.058
152	1.29	0.031
183	1.28	0.023
213	1.31	0.034
244	1.31	0.019