EVALUATING FORAGE SORGHUM AND PEARL MILLET FOR FORAGE PRODUCTION AND QUALITY IN THE TEXAS HIGH PLAINS

by

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ABSTRACT

As water levels in the Ogallala Aquifer continue to decline in the Texas High Plains, alternative forage crops that utilize less water must be identified to help meet the forage demands of the livestock industry in the region. The purpose of this two year study was to evaluate forage sorghum [*Sorghum bicolor* (L.) Moench] and pearl millet [*Pennisetum glaucum* (L.) Leeke] for forage production and quality. Three different harvesting regimes were implemented to evaluate forage productivity and regrowth of both crops throughout the 2016 and 2017 growing seasons. These different regimes included: three 30 day, two 45 day, and one 90 day harvest. Pearl millet and forage sorghum total dry matter production in 2016 ranged from 3.96 to 6.28 Mg DM ha^{-1} and 5.38 to 11.19 Mg DM ha^{-1} and in 2017 ranged from 6.00 to 9.87 Mg DM ha^{-1} and 6.53 to 15.51 Mg DM ha^{-1}, respectively. A 90 d harvest in the Texas High Plains will maximize water use efficiency and DM production; however, some forage quality may be sacrificed.

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CHAPTER 1

LITERATURE REVIEW

History of Forage Sorghum

Sorghum [*Sorghum bicolor* (L.) Moench] originated in Africa and has been domesticated over thousands of years (Smith & Frederiksen, 2000). Sorghum most likely entered the USA via the African slave trade and by the end of the 19th century, it was established on the Great Plains (Smith & Frederiksen, 2000) Sorghum found a home in the Southern High Plains because it is one of the world's most drought and heat tolerant crops (Smith & Frederiksen, 2000). Stated by Smith and Frederiksen (2000), sudangrass [*Sorghum bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan] was originally introduced in 1909 from Sudan as a grazing type forage sorghum and received wide acceptance in Texas. Sorghum-sudangrass hybrids are grown on over 101,171 ha in Texas (Sanderson et al., 1995). Sudangrass has been a staple in the Great Plains ever since for grazing, green chop, haying and silage crop management practices.

History of Pearl Millet

It is believed that pearl millet [*Pennisetum glaucum* (L.) Leeke] originated from northern Africa in the region of western Sudan to Senegal (Harlan and de Wet, 1971). Pearl millet is a major grain crop in India, Pakistan, and the countries of Africa, although it is mainly grown for forage in the USA (Hanna et al., 2004). According to Ball (1903), pearl millet was probably brought into the U.S. about the same time as sorghum and cultivated in the southeastern U.S. Pearl millet is adapted to poor, droughty, and infertile soils (Hanna et al., 2004), which suits it well in the Texas high plains.

Dry Matter and Yield

In forage sorghum, maximum forage yield occurs when the crop is at the hard dough stage (Pedersen & Rooney, 2004). Sudangrass has small diameter stems, great tillering capacity, very leafy, and has rapid growth potential, while tall forage sorghums have high dry matter yields, large diameter stalks, limited tillers, and limit in regrowth capabilities (Smith & Frederiksen, 2000). Sorghum sudangrass hybrids are in-between sudangrass and tall forage sorghum types in texture, while still retaining a high yield potential (Smith & Frederiksen, 2000). However, in a field study in 1987 and 1988 conducted in Normal, AL, Bishnoi et al. (1993) found that pearl millet can produce 1.5 to 2 times the amount of dry matter when compared to sorghum-sudangrass and grain and forage sorghums. The pearl millet dry matter yield averaged 13.3 DM Mg ha^{-1}, while sudangrass, grain sorghum, and forage sorghum had average yields of 6.9, 6.4, and 6.2 Mg DM ha^{-1}, respectively (Bishnoi et al., 1993).

A field study conducted in several locations across central and southern Illinois in 2009 and 2010 tested forage sorghum responses to nitrogen fertilization. A summer and a ratoon, fall harvest was used along with five different nitrogen (N) fertilizer treatments, 0, 56, 112, 168, and 224 kg ha^{-1} were used (Maughan et al., 2012). Under the five N treatments, 0, 56, 112, 168, and 224 kg N ha^{-1}, the summer cut yielded 10.6, 12.4, 12.7, 13.8, and 13.6 Mg DM ha^{-1}, respectively. The ratoon, fall cut yielded much less, 5.1, 5.3, 4.9, 5.4, and 5.6 Mg DM ha^{-1} under the fertilizer treatments, 0, 56, 112, 168, and 224 kg N ha $^{-1}$, respectively.

A pearl millet cutting height and harvest timing field study was conducted in Manhattan, KS in 1979 and 1980. At a 15 cm stubble height, pearl millet forage yields were between 1.6 and 1.8 Mg DM ha^{-1} greater than the a 25 or 30 cm stubble height (Stephenson & Posler, 1984). In a three cut system, at a 15 cm stubble height, forage yield totals averaged across two years 5.4 Mg DM ha^{-1}. In both years in the second cut yielded the most, 2.7 and 2.1 Mg DM ha^{-1}, respectively. While, the third cut yielded the least, 1.2 and 1.3 Mg DM ha^{-1}, respectively. In 1980, a two cut system at the boot stage was evaluated with a total yield of 6.5 Mg DM ha^{-1}. Cut 1 out-produced cut 2, yields were 5.1 and 1.5 Mg DM ha^{-1}, respectively. Stephenson and Posler (1984) discovered that frequent harvests decreased total forage yield in pearl millet.

A field study was conducted in Urbana, IL in 1964 and 1965 evaluating yield, protein, nitrate and prussic acid content of sudangrass, sudangrass hybrids, and pearl millets harvested at different cutting frequencies and cutting heights. All varieties harvested three times per year produced on average 3.2 Mg DM ha^{-1} more than varieties harvested four times per year (Burger & Hittle, 1967). All varieties yielded 2.3 Mg DM ha^{-1} higher at a stubble height of 7.6 cm versus a 15 cm stubble height in a three cut system except for two pearl millet varieties in 1964. In 1964 and 1965, the sorghum x sudangrass varieties yielded an average of 15.3 and 14.8 Mg DM ha^{-1} while the pearl millet varieties yielded an average of 14.6 and 15.0 Mg DM ha^{-1}, respectively. Burger and Hittle (1967) also found frequent removal of above ground biomass decreases the regrowth potential independent of the crop variety.

In a field study conducted in Kazakhstan from 2008 to 2012, the selection of high yielding agrophytocenoses of coarse millet, sorghum, and sudangrass was evaluated for fodder lands. In the five year study, sorghum, sudangrass, and coarse millet yielded 6.0, 4.0, and 2.7 Mg DM ha^{-1}, respectively (Nasiyev, 2013).

Ratooning and Regrowth

Ratoon cropping is where a crop is harvested two or more times in a growing season from a single planting (Duncan & Gardner, 1984). Plants with a high tillering capacity after a harvest can be cut, under some scenarios, and permitted to regrow as a ratoon crop (Smith & Frederiksen, 2000). So regrowth can occur, a minimum of 15 cm of stubble should remain after harvesting (Marsalis, 2011). However, frequent harvests decrease regrowth (Stephenson & Posler, 1984).

A field study conducted in Georgia in 1980 and 1981 evaluated sweet sorghum ratoon cropping which also encompassed tillering capacity. Duncan and Gardner (1984), used a formula to evaluate the capability of a variety to produce a ratoon crop, which was ratoon efficiency (RE) = ratoon weight/total weight. Most of the cultivars in this study had a RE of 35 to 45. When a greater percentage of the total weight is made up of the ratoon crop than the first crop, a higher RE value will result.

A field experiment tested the ratoon cropping of forage sorghum for silage conducted in De Kalb, IL from 1989 to 1991. Five harvest stage treatments were used, mid-vegetative (1.2 m tall), late vegetative (1.5 m), boot (1.8 m), bloom-milk (2.1 m), and hard dough (2.1 m) stages and harvested for the first cut on 42, 50, 56, 70, and 92 days after planting, respectively (McCormick et al., 1995). The ratoon crop was harvested 106 days after planting and the cutting height was 10 cm. The mid-vegetative, late vegetative, boot, bloom, and hard dough first harvest yielded 3.0, 4.8, 5.4, 6.3, and 7.2 Mg DM ha^{-1}, while the ratoon cut yielded 3.5, 2.8, 2.4, 1.6, and 0.0 Mg DM ha^{-1}, respectively. This study reported that a primary and ratoon harvest may yield as much as one-third more DM than a single harvest at the hard dough stage.

The growth and fodder yield of pearl millet as a ratoon crop was researched in a field study for two growing seasons in 2009 and 2010 in Egypt. Different planting dates and fertilizer regimes were tested at a 10 cm cutting height and harvested at 5 to 10% heading (El-Lattief, 2011). The sowing date average DM yield for the first cut was 3.4 Mg DM ha^{-1}. The second and third cut averaged 3.9 and 2.4 Mg DM ha^{-1}, respectively. The different fertilizers had no effect within the different harvests. This study suggested a mid-May planting date to maximize the fodder yield.

In a field study conducted in India in 2008 and 2009, pearl millet fodder potential was evaluated in a multi-cut system. Two hybrids of pearl millet and one sorghum cultivar was sown and harvested 50 days after planting while ratoon cuts were taken at 30 day intervals after (Shashikala et al., 2013). This study reported pearl millet grows vigorously and accumulates more biomass with heavy tillering and with minimum irrigation than sorghum found in the area. One pearl millet variety yielded 5.0, 12.1, and 10.6 Mg DM ha^{-1} on the first, second, and third harvest, respectively. However, another pearl millet variety yielded 4.9, 8.0, and 5.9 Mg DM ha^{-1} on the first, second, and third cut, respectively. The sorghum cultivar generated 3.9, 4.9, and 4.6 Mg DM ha^{-1} on the first, second, and third harvest, respectively. The researchers observed DM yields from the second harvest were more than 50% higher than the first harvest and hypothesized that it might be credited to maximum tillering after the first fodder harvest.

Forage Quality

Forage sorghum and pearl millet are utilized for grazing, silage, and hay production because they are high quality forage crops (Hanna et al., 2004; Staggenborg, 2016). As the plant matures, lignification increases (Pedersen & Rooney, 2004; Smith & Frederiksen, 2000). This is strengthened by McCormick et al. (1995), which found that concentrations of lignin in first cut sorghum differed more than any other plant component as the crop matured.

Forage Sorghum Quality

Forage quality and agronomic traits of sorghum-sudangrass hybrids were assessed in a field study in Stephenville, TX from 1989 to 1991. The forage was harvested three times in 1989 and four times in 1990 and 1991 when the hybrids reached the panicle emergence stage with the average total biomass yield being 15.0 Mg DM ha^{-1} (Sanderson et al., 1995). Acid detergent fiber (ADF) and crude protein (CP) was analyzed using near infrared reflectance spectrometer (NIRS). Percent ADF varied across the years with 41.4, 33.8, and 34.3% in 1989, 1990, and 1991, respectively. The mean, across the three years, for CP was 10.9%.

A field study conducted in Bushland, TX assessed grain and forage sorghum production, water use and feed quality factors with no-tillage practices on dryland production from 1984 to 1986. One grain sorghum variety and five forage sorghum varieties were used. The forage sorghum averaged 8.6 Mg DM ha^{-1} with 7.1% CP (Unger, 1988).

Forage quality of ratoon cropping forage sorghum was assessed in De Kalb, IL in 1989 to 1991. This study contained five harvest treatments at mid-vegetative, late vegetative, boot, bloom, and hard dough with a ratoon harvest at 106 days after planting (McCormick et al., 1995). The five first harvests, mid-vegetative, late vegetative, boot, bloom, and hard dough CP values were 170, 136, 109, 94, and 66 g kg^{-1}, while the ratoon cut CP values were 86, 90, 92, and 100 g kg^{-1}, respectively. The hard dough harvest treatment did not have a ratoon cut. The ADF values for the five, first cut harvests, mid-vegetative, late vegetative, boot, bloom, and hard dough, were 357, 409, 458, 402, and 415 g kg^{-1}, while the ratoon cut ADF values were 346, 343, 349, and 340 g kg^{-1}, respectively. Neutral detergent fiber (NDF) values for the five, first harvests were 595, 636, 674, 650, and 610 g kg^{-1} while NDF values for the ratoon harvests were 615, 626, 619, and 630 g kg^{-1}. The research team found as maturity advances, the nutritive value of the first cut declined. This study reports to attain protein concentrations similar to high quality cool season grasses, it is pertinent to harvest forage sorghum earlier in a vegetative state.

Pearl Millet Quality

There is no risk of prussic acid poisoning with pearl millet (Hanna et al., 2004; Stephenson & Posler, 1984). According to Hanna et al. (2004), to maximize the digestible energy available, pearl millet should be harvested every 30 to 37 days.

In a field study conducted in Egypt, the growth and fodder yield of pearl millet affected by planting date and fertilizer scheme was evaluated in 2009 and 2010. The first cut, average sowing date CP value was 9.0%, while the second and third average cuts were 7.8 and 7.5%, respectively (El-Lattief, 2011). The sowing date and fertilizer regime interaction was not significant within CP results in the different harvests.

A field study was conducted in Karaj, Iran in 2007 evaluating forage quality, water use and nitrogen fertilization efficiencies of pearl millet grown under different soil moisture and nitrogen levels. Four different irrigation treatment levels, 40, 60, 80, and 100% depletion of total available water and four different nitrogen fertilizer treatment levels, 0, 75, 150, and 225 kg N ha^{-1}, were arranged in a 4 x 4 factorial (Rostamza et al., 2011). The data for stem and leaf, and total DM are a sum of three harvests while total digestible nutrients (TDN), CP, and ADF are averaged over the three harvests. This study reported as water was limited, CP and ADF increased. Irrigation levels 40, 60, 80, and 100% contained 15.6, 15.9, 17.4, and 19.2% CP and 32.8, 33.0, 37.8, and 36.4% ADF, respectively. However, TDN decreased as available water decreased. The irrigation treatments 40, 60, 80, and 100 contained 54.7, 54.5, 53.2, and 51.4% TDN, respectively. This study also reported as more nitrogen was applied, CP increased. The four nitrogen levels, 0, 75, 150, and 225, produced forage with 15.1, 16.4, 17.6, and 19.0% CP, respectively.

The feeding value of pearl millet influenced by the brown midrib trait (BMR) was evaluated in a field study near West Lafayette, IN in 1989. A BMR and normal, non-BMR variety of pearl millet was harvested 46 DAP and a ratoon harvest was made 98 DAP (Cherney et al., 1990). The normal variety contained 67.4 and 66.5% NDF in the first and second cutting, respectively. However, the BMR variety contained 67.7 and 62.3% NDF in the first and second cutting, respectively. In ADF, the normal genotype contained 34.3 and 34.5% in the first and second cutting, while the BMR genotype contained 34.5 and 31.4% in the first and second cutting, respectively. The BMR variety had lower % ADF and NDF in the second cut than the non-BMR variety. Crude protein was also higher in the BMR type for both cuttings. The first and second cuttings of the normal type contained 12.8 and 10.2% CP, while the BMR type contained 14.6 and 12.3% CP, respectively.

In Tifton, GA, the seeding method effects on pearl millet forage quality and the performance of grazing beef heifers was evaluated in a field study in 1992 and 1993. Pearl millet was drilled at 0.25 m or planted in 0.91 m rows and leaf samples were hand harvested and CP, ADF, NDF, and TDN were reported (Hill et al., 1999). The drilled seeding method reported 24.3, 23.5, 53.3, 74.0% CP, ADF, NDF, and TDN, respectively. The row seeding method contained 23.5, 26.6, 53.6, and 71.7% CP, ADF, NDF, and TDN, respectively. This study stated the leaf samples had generally lower ADF and NDF and higher TDN than samples from cannulated steers due to the fact there were no stems present in the leaf samples.

In a field study in 2008 to 2012, coarse millet, sorghum, and sudangrass were evaluated in Kazakhstan and contained 3.6, 2.4, and 3.0% CP, respectively (Nasiyev, 2013).

Brown Midrib Trait

Characteristics of the BMR trait include a noticeable brown pigment in the midrib of the leaves, stems, pith, and immature panicles of the plant (Porter et al. 1978). Forages that contain the brown midrib trait contain less lignin which improves forage digestibility for livestock (Oliver et al., 2005; Sattler et al., 2010). However, BMR hybrids have reduced yield (Porter et al., 1978).

A field trial conducted in Nebraska in 2002 and 2003 researched two brown midrib genes, bmr-6 and bmr-12, in forage sorghum. The wild type produced a shorter plant than both BMR genes, bmr-6 and bmr-12, 194, 211, and 215 cm, respectively (Oliver et al., 2005). The wild type also produced more forage, 15.0 Mg DM ha^{-1}, than bmr-6 and bmr-12, 12.8 and 13.5 Mg DM ha^{-1}, respectively. There was no significant difference in NDF quality across the treatments, but a difference in ADF quality was reported. The ADF values for the wild type, bmr-6, and bmr-12 are 269, 262, and 268 g kg^{-1}, respectively.

Forage Antiquality

Both forage sorghum and pearl millet are nitrate accumulators (Smith & Frederiksen, 2000). In a field study conducted in Urbana, IL in 1964 and 1965, Yield, protein and nitrate content was assessed in sudangrass and pearl millet at two different stubble heights and two cutting frequencies. Burger and Hittle (1967) found that nitrate accumulation in sudangrass and pearl millet is significantly higher when harvested at 7.6 cm compared to a 15.2 cm stubble height in both, a three cut and four cut system. This is accredited to the observation that greater nitrate content is found in the stems than in the leaves. At a 7.6 cm cutting height, the three cut system across both years averaged 2797 ppm of nitrate nitrogen while the four cut averaged 2988 ppm of nitrate nitrogen. The 15.2 cm harvest height in the three cut system averaged 2322 ppm of nitrate nitrogen while the four cut system averaged 2406 ppm of nitrate nitrogen.

Leaf Area Index

Leaf area index (LAI) is the leaf area per unit soil area ($cm^2 \cdot cm^{-2}$) (Fageria et al., 2006). In a field study conducted in central and southern Illinois in 2009 and 2010, LAI was evaluated in energy sorghum. This study reported in 2009 an end of season LAI estimate of 3.1 when no nitrogen fertilizer was applied (Maughan et al., 2012). However, with 100 kg N ha^{-1} applied in 2009, LAI reached an estimated 4.2. At the end of the 2010 season, LAI reached a value of 5.0; however, when no fertilizer was applied, the LAI was still lower with an estimated value of 4.5.

A field study conducted in Hisar, India assessed agronomic and physiological responses of forage sorghum, maize and pearl millet to irrigation in 1979 and 1980. In 1980, four irrigation treatments were used: an unstressed, a mildly stressed, a moderately stressed, and a severely stressed. The seasonal means for the LAI of unstressed sorghum and pearl millet in 1980 were 6.4 and 11.4, respectively (Singh & Singh, 1995). The LAI values for the severely stressed crops reduced 62 and 43% over the unstressed sorghum and pearl millet, respectively.

A field study in 2007 conducted in Karaj, Iran researched the forage quality, water use and nitrogen utilization efficiencies of pearl millet grown under different soil moisture and nitrogen levels. The LAI values were 8.65, 7.89, 6.45 and 4.19 under the irrigation treatments, 40, 60, 80, and 100% depleted total available soil water, respectively (Rostamza et al., 2011). Under the four N fertilizer treatments, 0, 75, 150, and 225 kg N ha^{-1}, LAI values were 5.59, 6.58, 7.31, and 7.69, respectively. As water is restricted, LAI decreases. However, as N fertilizer is applied, LAI increases.

Photosynthetic Active Radiation

"The rate of photosynthesis is dependent upon the quantum content of radiation in the photosynthetically active waveband, 0.4 – 0.7 µm" (Marshall and Willey, 1983).

In an energy sorghum field trial conducted in Urbana, IL in 2009 and 2010, intercepted photosynthetic active radiation (PAR) was evaluated. In both years, PAR reached an estimated 95% interception (Maughan et al., 2012). This study reported a high correlation of 0.93 and 0.95 of LAI to PAR in 2009 and 2010, respectively.

A field study conducted at the Cropping Systems Section at the International Crops Research Institute (ICRISAT) in 1978 researched the radiation interception and growth in an intercrop of pearl millet and groundnut. Marshall and Willey (1983), found a positive correlation between dry matter of pearl millet and intercepted PAR throughout the vegetative and most of the reproductive phases. The amount of light energy intercepted into dry matter equaled 4.1 g MJ^{-1} and was maintained until the first half of grain fill, where it began to decrease (Marshall and Willey, 1983).

The refractometric determination of sucrose levels in the stubble of sudangrass and pearl millet was assessed in a field study conducted in University Park, PA in 1959 and 1960. The researchers found plants harvested at 15 or 20 cm stubble height had adequate remaining photosynthetic tissue to meet the needs of the plant requirements for positive growth (Mays & Washko, 1962). However, plants that were harvested at 5 and 10 cm stubble height consumed more reserve material for new growth.

Plant Height and Morphology

Forage Sorghum

Forage sorghum grown for forage production is often 2 to 3 m in height but can reach heights of 4 to 6 m (Pedersen & Rooney, 2004; Smith & Frederiksen, 2000). According to Smith and Frederiksen (2000), sorghum has a fibrous root system that can penetrate the soil 1.5 to 2.4 m. If a hard pan is present, the roots will be in the top 0.9 m of the soil and the roots have the potential to reach out a meter or more from the stem (Smith & Frederiksen, 2000).

A forage sorghum yield and water use efficiency under variable irrigation field study was assessed in Shambat, Sudan in 1982 and 1983. Three different irrigation treatments were used including: a light frequent (A), a moderate less frequent (B), and a heavy infrequent (C) regime where plants were watered every 7, 10, and 13 days, respectively (Saeed & El-Nadi, 1998). Average stem heights for A, B, and C reached 150, 145, and 135 cm in 1982 and 180, 150, and 135 cm in 1983, respectively.

In a field study conducted in Georgia in 1980 and 1981, the influence of ratoon cropping on sweet sorghum yield, sugar production, and insect damage was assessed. This study found that the ratoon crop height varied from 75 to 91 percent of the first crop (Duncan & Gardner, 1984).

Pearl Millet

Pearl millet can range from 1.5 to 3 m tall, but can reach heights of 5 m (Hanna et al., 2004). A field study in 1987 and 1988 conducted in Normal, AL evaluated the quantity and quality of forage and silage of pearl millet in comparison to sorghum-sudangrass, grain sorghum, and forage sorghum harvested at different growth stages. Pearl millet was significantly taller than the sorghums tested (Bishnoi et al., 1993). Pearl millet, sudangrass, grain sorghum, and forage sorghum averaged a height of 271, 190, 88, and 179 cm, respectively.

Marshall and Willey (1983), found a monocrop of pearl millet produced 1.3 tillers per plant. However, in a multi-harvest field study conducted in Egypt, pearl millet produced, on average, 10.3 tillers per plant right before the first harvest (El-Lattief, 2011). At the second and third harvest, 13.9 and 17.5 tillers per plant, respectively, were reported. This study also reported plant height; the first, second, and third harvest reached 135, 142, and 137 cm, respectively.

In a field study conducted in Raleigh, NC, the impact of different defoliation systems on the regrowth of pearl millet, sudangrass and sorghum-sudangrass from the terminal, axillary, and basal buds was evaluated in 1966 and 1967. This study reported stubble heights at 8 or 10 cm of summer, annual grasses post-harvest, encouraged better tiller initiation and reduced the contribution from continual terminal growth (Clapp et al., 1970).

Crop Growth Rate and Growing Degree Days

Crop growth rate can be defined as dry matter accumulation rate per unit land area (Fageria et al., 2006). The leaf/stem ratio decreases as plant maturity advances (Pedersen & Rooney, 2004).

Sorghum sudangrass hybrids will typically have leaf/stem ratios lower than 50% (Smith & Frederiksen, 2000). As maturity advances, leaf/stem ratio lowers (Smith & Frederiksen, 2000).

In pearl millet, the leaf/stem ratio tends to be greater than 50/50 (Marsalis et al., 2012). A water use and nitrogen utilization efficiency of pearl millet grown under different soil moisture and nitrogen levels field study in 2007, conducted in Karaj, Iran, found supportive results for leaf/stem ratios. Under four different irrigation levels, 40, 60, 80, and 100% of depleted total available soil water, the leaf/stem ratio was 1.6, 1.8, 2.0, and 2.6, respectively (Rostamza et al., 2011).

A field study tested the yield and quality of three pearl millet varieties harvested at different growth stages in 1994 and 1995 in Shika, Nigeria. The leaf/stem ratio was 0.5 for all accessions and growth stages (Amodu et al., 2001). This differs from results from Marsalis et al. (2012) and Rostamza et al. (2011). This experiment concurs with results found in a field study conducted in Normal, AL in 1987 and 1988. The leaf/stem ratios of pearl millet, sudangrass, grain sorghum, and forage sorghum were 0.6, 0.43, 1.77, and 0.47, respectively (Bishnoi et al., 1993).

A field study in 2004, 2005, and 2006 conducted in El Reno, OK evaluated forage and biomass production feedstock production from hybrid forage sorghum and sorghum-sudangrass hybrids. A 10°C minimum and 30°C maximum temperature was used to calculate growing degree days, GDDs, (Venuto & Kindiger, 2008). However, in a two year, pearl millet production, field study near Mead, NE conducted in 1995 and 1996, a base temperature of 12°C was used (Maman et al., 1999).

Thermal time was estimated in a simulation of sorghum and pearl millet in a growth chamber study of several sorghum genotypes. Using scores for leaf tip appearance as a signal of the state of plant growth, 8°C was identified as the base temperature, while the maximum temperature was designated as 34°C (Virmani et al., 1989). This growth chamber study was also reported by Alagarswamy and Ritchie (1991).

Water Use Efficiency

Water use efficiency (WUE) is defined as the amount of biomass accumulated per unit of water used (Fageria et al., 2006). Singh and Singh (1995), found pearl millet to have a greater WUE than sorghum under drought conditions, 17.9 and 14.4 kg ha^{-1} mm^{-1}, respectively.

Forage Sorghum WUE

A field study in Shambat, Sudan in 1982 and 1983 researched forage sorghum yield and water use efficiency under variable irrigation. Three irrigation treatments were used with two pre-experimental irrigations totaling 70 mm of water and 700 mm of total water used in the experiment (Saeed & El-Nadi, 1998). Treatment A had ten irrigations with 56 mm per irrigation, treatment B had seven irrigations with 80 mm per irrigation, and treatment C had five irrigations with 104 mm per irrigation. Treatments A, B, and C averaged 85.5, 76.5, and 69.5 kg ha^{-1} mm^{-1}, respectively. In both years, forage sorghum yields were taken 90 days after planting. In 1982, treatment B and C were close together producing and average of 11.0 Mg DM ha^{-1}, while treatment A produced 14.0 Mg DM ha^{-1}. In 1983, treatment C produced the least with 10.0 Mg ha^{-1}, treatment B yielded 12.0 Mg DM ha^{-1}, and treatment A yielded the most at 18 Mg DM ha^{-1}. Saeed and El-Nadi (1988), recommend in semiarid environments, forage sorghum should be irrigated lightly and frequently to get the best yields and WUE.

From 1984 to 1986 a field study was conducted in Bushland, TX assessing water use efficiency and production of grain and forage sorghum with no-tillage practices on dryland. Unger (1988), found that forage sorghums used less total water and utilized the water more efficiently for yield and CP than grain sorghums. Water use efficiency averaged 2.9 kg DM m^{-3} for forage sorghum, while WUE for grain sorghum was 2.2 kg DM m^{-3}.

Pearl Millet WUE

A field study assessed forage quality, water use and nitrogen fertilization efficiencies of pearl millet grown under different soil moisture and nitrogen levels conducted in Karaj, Iran in 2007. This field was arranged in a 4 x 4 factorial with four irrigation treatments and four N fertilizer treatments (Rostamza et al., 2011). The four irrigation treatments were based on depletion of total available soil water, 40, 60, 80 and 100%. The fertilizer levels were 0, 75, 150, and 225 kg ha^{-1}. Water use efficiency was averaged over three harvests and based on total evapotranspiration. As water was restricted, WUE in pearl millet increased. Under the four irrigation levels, 40, 60, 80, and

100% depletion of total available soil water, WUE was 2.84, 3.02, 3.32, and 3.44 kg DM m^3, respectively. As N increased in the four N treatments, 0, 75, 150, and 225 kg N ha^{-1}, WUE increased, 2.75, 3.08, 3.42, and 3.36 kg DM m^3, respectively

CHAPTER 2

EVALUATING FORAGE SORGHUM AND PEARL MILLET FOR FORAGE PRODUCTION AND QUALITY IN THE TEXAS HIGH PLAINS

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Abstract

As water levels in the Ogallala Aquifer continue to decline in the Texas High Plains, alternative forage crops that utilize less water must be identified to help meet the forage demands of the livestock industry in the region. The purpose of this two year study was to evaluate forage sorghum [*Sorghum bicolor* (L.) Moench] and pearl millet [*Pennisetum glaucum* (L.) Leeke] for forage production and quality. Three different harvesting regimes were implemented to evaluate forage productivity and regrowth of both crops throughout the 2016 and 2017 growing seasons. These different regimes included: three 30 day, two 45 day, and one 90 day harvest. Pearl millet and forage sorghum total dry matter production in 2016 ranged from 3.96 to 6.28 Mg DM ha^{-1} and 5.38 to 11.19 Mg DM ha^{-1} and in 2017 ranged from 6.00 to 9.87 Mg DM ha^{-1} and 6.53 to 15.51 Mg DM

ha^{-1}, respectively. A 90 d harvest in the Texas High Plains will maximize water use efficiency and DM production; however, some forage quality may be sacrificed.

Introduction

Alternative forage crops that utilize less water must be identified to meet the demands of the livestock industry in the region as water levels in the Ogallala Aquifer continue to decline in the Texas High Plains. Forage sorghum [*Sorghum bicolor* (L.) Moench] is widely utilized in the High Plains region because of its drought and heat tolerance. Sorghum has the potential to produce large amounts of nutritious forage during summer months and their versatility allows them to fit into many different types of cropping or livestock operations (Marsalis, 2011). However, pearl millet [*Pennisetum glaucum* (L.) Leeke] may have the potential to meet some of these forage needs.

Regrowth of pearl millet is affected by stubble height, cutting frequency, and stage of harvest (Stephenson and Posler, 1984). Unlike many sorghums, pearl millet contains no prussic acid (Stephenson and Posler, 1984). Both species have varieties that contain the brown midrib trait; therefore, they have reduced lignin to increase forage quality and give producers more flexibility in harvest scheduling (Staggenborg, 2016).

Therefore, pearl millet might have the opportunity to be as productive as forage sorghum and provide the same quality. Cutting height and yield attributes of pearl millet and forage sorghum have been evaluated in Kansas and New Mexico, but not in the Texas High Plains (Marsalis, 2011; Stephenson and Posler, 1984). However, additional information is required to find the best cutting interval to optimize yield and quality in the region. The objectives of this study were to i) evaluate forage sorghum and pearl millet forage production and regrowth patterns under three different harvest intervals, and ii) evaluate the effects of harvest interval on feed nutritive components and value.

Materials and Methods

This study was conducted during the 2016 and 2017 growing seasons at the West Texas A&M University Nance Ranch near Canyon (34°58’6”N, 101°47’16” W; 1097 m above sea level).

Fields with Olton clay loam soil (fine, mixed, superactive, thermic, Aridic Paleustoll) were prepared for planting with two passes of a tandem disk followed by one pass with a rotary tiller. ‘Bodacious’ BMR sorghum sudangrass (7272 seeds kg^{-1}, 85% germination, 98% purity) and ‘Graze King’ BMR pearl millet (176211 seeds kg^{-1}, 85% germination, 98% purity) were planted at 67 seeds m^{-2} on 25 May 2016 using a tractor mounted 150 cm wide Great Plains 3P500 grain drill (Great Plains Manufacturing, Salina, KS) with 19-cm row widths. On 15 June 2016 both species were terminated with Roundup PowerMax herbicide glyphosate at a rate of 0.95 ml m^{-2}. Both species were replanted at a higher rate on 17 June 2016 because of inadequate stands. The BMR sorghum sudangrass was planted at a rate of 75 seeds m^{-2} and the BMR pearl millet was planted at 85 seeds m^{-2}. In 2017, a pearl millet seed lot (116280 seeds kg^{-1}, 85% germination, 98% purity) was acquired from Winfield United. On 31 May 2017 both species were planted with the same rate. Main plot size was 24.4 by 18.2 m. The planted area for each sub plot was 3 by 6.1 m in both years.

The crops were irrigated the same with a flow metered drip line system with two lines 152 cm apart and drip line emitters every 61 cm. The emitters applied 7.5 L hour and 25 mm of water was applied weekly for 10 weeks. Urea nitrogen fertilizer was broadcast applied based on soil sampling recommendations on 12 July 2016 and 7 July 2017 at 84 kg N ha^{-1} and 78 kg N ha^{-1}, respectively.

Harvest Interval and Yield

Forage DM was sampled in three harvest regimes: three 30 d, two 45 d and one 90 d harvest. Samples were cut at 15 cm cutting height using a one meter quadrat. Two samples were taken per plot and averaged together. Ratoon harvests were taken from the same sampled area each time. Samples were oven dried at 60°C for 120 h.

Leaf Area Index

Leaf Area Index (LAI) was determined every 14 days and after each harvest beginning on 12 July 2016 and 21 June 2017 using Li-Cor 2200 plant canopy analyzer (Li-Cor Incorporated, Lincoln, NE). Two LAI measurements were obtained in each plot. A LAI measurement is defined as one above canopy (incident) reading and four below canopy readings. The four below canopy readings were taken across three rows and averaged for one LAI value. Measurements were collected under low light at sunrise, sunset, or overcast conditions.

Light Interception

Photosynthetically active radiation (PAR) interception by the forage canopy was determined every 7 d beginning on 6 July 2016 and 21 June 2017 using AccuPAR Linear PAR Ceptometer, Model PAR-80 light measuring instrument (Decagon Devices, Pullman, WA). Measurements were obtained by placing the ceptometer diagonally across three rows. Measurements were collected under full sunlight between 1100 and 1400 h. Percent light interception was calculated by dividing the average of two below canopy PAR readings by one above canopy reading and multiplying by 100.

Plant Density and Growth

Crop growth rate and development was determined by measuring plant height, plant and tiller density and above ground biomass every 7 d starting on 6 July 2016 and 21 June 2017. Plant height was determined by averaging two 0.25 m^{-2} quadrat measurements in each plot. Plant and tiller density was determined from non-trafficked areas with a 0.10 m^2 quadrat. The AGB was determined by sampling in a non-trafficked, randomly selected 0.10 m^2 quadrat. Stems and leaf blades were separated from the sample and weighed independently after being oven dried at 70 C for 48 h.

Forage Analysis

Forage analysis samples were taken from biomass samples, ground with a wood chipper and sent to Servi-Tech Laboratories. Samples were ground through a Wiley mill (Arthur H. Thomas Co., Philadelphia, PA) to pass a 1-mm screen. Crude protein, ADF, NDF, TDN, and relative feed value (RFV) were analyzed.

Crude protein was found using the combustion method, an AOAC Official Method 990.03 (AOAC International, 2012). The ADF analysis was found using Ankom technology method 5 (Ankom, 2006). This method is a modification of AOAC Official Method 973.18. The NDF analysis was done with Ankom technology method 6, a modification of AOAC Official Method 2002.04 (Ankom, 2006). Total digestible nutrients is found using the formula: TDN = (NFC x 0.98) + (CP x 0.87) + (FA x 0.97 x 2.25) + (NDFn x NDFDp / 100) – 10.

The RFV is a calculation of digestible dry matter (DDM) and dry matter intake (DMI) and a constant. The RFV is found by using the formula as follows: RFV = (DDM x DMI) / 1.29. The DDM is calculated by using the formula: DDM = 88.9 – (0.779 x %ADF). DMI is calculated by using the formula: DMI = 120 / %NDF.

Water Use Efficiency

Water use efficiency (WUE) measurements were taken in the 2017 growing season only. Plant available soil water (PAW) at planting was taken in adjacent plots less than 50 m away from four random sites to a depth of 75 cm using a tractor mounted Giddings hydraulic press (Giddings Machine Company Inc., Windsor, CO). The soil core samples were divided into three depth sectors: 0 – 15, 15 – 45, and 45 – 75 cm. One core sample per plot, divided into three depth sectors: 0 – 15, 15 – 45, and 45 – 75 cm, was taken at end-of-season harvest to determine PAW, weighed, then oven dried at 104°C for 72 h. The PAW was found using the equation: PAW = [(volumetric water – permanent wilting point) / 100) x depth in cm of the measured soil profile]. The WUE was calculated using the following formula: WUE = DM / [(PAW planting + total rainfall + total irrigation) – PAW harvest].

Weather Data

Weather conditions during the study in 2016 and climatic data were obtained from the National Weather Service Forecast Office (Amarillo, TX). In 2017, daily maximum and minimum air temperature and rainfall were recorded from a weather station

(Campbell Scientific, Logan, UT) located 100 m from the experimental site (Table 1). Canyon, TX has a mean annual rainfall of 474 mm. Growing degree days (GDD) were calculated beginning June 2016 and May 2017 of each season using the formula: GDD = Σ {[(daily max. temp. + daily min. temp.) / 2] – base temp.} with base temperature = 10°C, and maximum temperature = 34°C (Venuto & Kindiger, 2008; Virmani et al., 1989).

Statistical Design and Analysis

The experiment had a nested split plot design. Statistical analysis was performed using the PROC MIXED of the Statistical Analysis System Version 9.4 (SAS Institute, 2017). A LSD/PDIFF ($\alpha = 0.05$) was used to test significant differences between treatment means unless otherwise noted.

Results and Discussion

Weather Conditions

The 2016 growing conditions were unfavorable due to warmer temperatures in June and July and cooler temperatures, 6.9 and 6.1°C below the average in August and September (Table 1). For the month of June, in 2016, only 35% of the 30 year average rainfall accumulated. However, in 2017 growing conditions were similar to the 30 year average. June through September averaged 145% more precipitation than the 30 year average. In 2016, both crops accumulated 134 GDDs before the crops emerged, although in 2017, 161 GDDs were accumulated. The 2016 growing season accumulated 1461 GDDs while in the 2017 growing season, 1377 GDDs were accumulated.

Biomass and Yield

The maximum amount of forage was produced in the 90 d harvest interval in 2016 and 2017 in forage sorghum, 11.05 and 15.51 Mg DM ha^{-1}, and in pearl millet, 6.26 and 9.87 Mg DM ha^{-1}, respectively (Figure 1). When total DM harvest intervals were averaged, pearl millet only produced 70% of the average total forage sorghum DM. However, Bishnoi et al. (1993) found that pearl millet can produce 1.5 to 2 times the amount of forage compared to sorghum-sudangrass and forage sorghum. This can be attributed to an average, growing season rainfall of 520 mm in Normal, AL in 1987 and 1988. In 2016, the forage sorghum yields for the 30 d and 45 d harvests ranged from 48 – 45% of the 90 d harvest. While in 2017, 30 d and 45 d harvests ranged from 42 – 45% of the 90 d harvest.

In 2016, pearl millet yields for the 30 d and 45 d harvests ranged from 63 – 60% of the 90 d harvests (Table 2). While in 2017, 30 d and 45 d harvests ranged from 60 – 57% of the 90 d pearl millet yields. This is contrary to Stephenson and Posler (1984) that found pearl millet to produce 83% of total DM when comparing a three cut system to a two cut system when harvested at the boot stage.

The forage sorghum, 45 d harvest ratoon cut responded differently in both years. There was no difference between the first cut and the ratoon harvest in the first year, while in 2017, more forage was produced in the first harvest. This can be attributed to above average rainfall in June and July of 2017. In 2016, the ratoon cut made up 47% while in 2017, the ratoon cut made up 35% of the total DM yield. This is higher when compared to Maughan et al. (2012) that had a ratoon cut that yielded 29% of the total DM produced. However, this study is similar to a study conducted by Duncan and Gardner (1984) that found cultivars to have a ratoon efficiency range from 35 to 45%.

In both years, the pearl millet 30 d harvest intervals responded similarly with 13 – 15% of the total DM yielding from the first cut and 64 – 67% produced from the second cut. This differs from Stephenson and Posler (1984) that found 33% of the total forage DM yielding from the first cut while the second cut yielded 44% of the total forage DM. However, the third cut did respond correspondingly to Stephenson and Posler (1984) with 23% of the DM produced from the third harvest. Therefore, most of the growth, in this study, was produced between 30 and 60 days.

Forage Quality

In the 30 d interval, forage sorghum; CP averaged across harvests, 10.2 and 10% in both years, respectively (Table 2). This is similar to results found by Sanderson et al. (1995) that reported an average of 10.9 % CP. Crude protein did not differ in 2016 and in 2017, CP decreased slightly. This is contrary to El-Lattief (2011) that reported decreasing CP at each harvest, 9.0, 7.8, and 7.5% CP, respectively. Sanderson et al. (1995) also reported an ADF of 36.5% when harvests are averaged together. Their findings were similar to this study that reported forage sorghum ADF as 35.8 and 38% when averaged across the three harvest intervals in 2016 and 2017, respectively.

Forage sorghum, in the 45 d harvest, had higher CP and RFV in the ratoon cut but lower TDN. However, in 2017, a higher CP was found in the first harvest. In the 90 d harvest, only the dry matter differed in both years between crops except for NDF in 2017.

This study reported slightly better %CP than Nasiyev (2013) that reported 3.6, 2.4, and 3.0% CP in course millet, sorghum, and sudangrass, respectively.

In the 45 d harvest, pearl millet had higher CP and TDN in the first harvest compared to the ratoon harvest. However, only in 2016, the first harvest had a higher RFV. This study reported slightly lower NDF% when compared to Cherney et al. (1990) that found BMR pearl millet to contain 67.7 and 62.3% NDF in the first and second harvest, respectively. On the contrary, Cherney et al. (1990) reported lower ADF% in the first and second cut of 34.5 and 31.4% ADF, respectively. Crude protein content conveyed by Cherney et al. (1990) is similar to 2016. The 2016 %CP for each cut is 14.8 and 12.0% compared to 14.6 and 12.3% CP reported by Cherney et al. (1990) for the first and second harvest, respectively. The CP of the first and second harvest in 2017 were two and fifty percent lower than values reported by Cherney et al. (1990), respectively.

In both years, the pearl millet, 30 d harvest interval %CP decreased with each harvest. When averaged across the three harvests, CP is 6% lower than reported by Rostamza et al. (2011). In 2016, both ADF and NDF increased with each harvest; however, only ADF increased in 2017 while NDF declined. This is contrary to Rostamza et al. (2011) that found as water is limited, ADF increases. Rostamza et al. (2011) reported TDN decreases as available water decreases; however, in this study, rainfall was less in 2016 but had 5% higher TDN than 2017 when averaged across harvests. At the third harvest, in 2016, RFV declined but in 2017, RFV increased from the second harvest.

As both crops advanced in maturity, an overall decline in forage quality can be noted. This is attributed to a decline in the leaf:stem ratio in both crops (Figures 9 & 10).

When the leaf:stem ratio degenerates, more mass is allocated in the stem; thus more lignin is produced and lowering the forage quality.

Crop Canopy Development

Leaf Area Index

The 90 d, forage sorghum harvest responded similarly in both years, plateauing between 1078 and 1029 GDDs (Figures 3 & 4). However, 2016 had a 3% higher end of season LAI value, 4.65, when compared to 4.50 in 2017. This is similar to LAI values of 4.5 to 5.0 in the 2010 growing season reported by Maughan et al. (2012). However, the 2016 and 2017 study are much lower than Singh and Singh (1995) that reported a LAI value of 6.4.

In 2016, the 90 d pearl millet harvest reached maximum LAI, 3.95, at 1078 GDDs and ended the season at a LAI of 3.83. However, LAI in 2017 peaked at a value of 5.64 at 1029 GDDs and sloped off at the end of the season to a LAI of 4.61. This study is much lower than results found by Singh and Singh (1995) that reported LAI values of 11.4 and 6.5 in unstressed and severely stressed pearl millet, respectively. Singh and Singh (1995) attributed this to the severely stressed plants having higher ground cover due to the death of the lower leaves and the incident interception of the upper profile of the crop canopy.

In both years and both crops, the 45 d harvest had a higher LAI value before harvest than at the end of the season. A similar trend occurred in the 30 d harvest interval where maximum LAI was attained before the second harvest. The forage sorghum, 30 d harvests recovered from the maximum LAI to the end of season LAI, 52% and 47% in 2016 and 2017, respectively. While, 30 d harvest, pearl millet recovered 57% and 54% in both years after the second harvest. In 2016, both forage sorghum and pearl millet recovered 93 and 98% of the maximum LAI; however, in 2017, only 88 and 73% of the LAI value was recovered in forage sorghum and pearl millet, respectively.

Photosynthetic Active Radiation

In 2016, pearl millet; end of season light interception ranged 20% between the three cutting intervals (Figure 5). The 30, 45, and 90 d harvest intervals had end of season PAR interception at 67, 77, and 87% PAR, respectively. In both years, pearl millet reached maximum PAR, 90 and 98%, 350 GDDs before the final harvest (Figures 5 & 6). However, forage sorghum in both years reached maximum PAR, 94 and 96%, 200 GDDs after pearl millet reached maximum PAR interception. This is similar to Maughan et al. (2012) that found energy sorghum reached 95% PAR interception.

In 2016, both species in the 45 d harvest reached 82% PAR before harvest; while in 2017, both crops averaged 93% intercepted PAR before harvest. In 2017, pearl millet seemed to have higher light interception after harvest. This can be attributed to having a higher LAI value, leaf:stem ratio, and tillers per plant.

Across both species and years in the 30 d harvest interval, maximum PAR was achieved right before the second harvest. The forage sorghum peaked at 90 and 94% and pearl millet peaked at 81 and 98% PAR in both years, respectively.

Plant Morphology

Pearl millet at the 90 d harvest interval had no less than three tillers per plant at the end of the season (Figures 7 & 8). This is contrary to Marshall and Willey (1983) that reported a monocrop of pearl millet produced 1.3 tillers per plant. However, in a three harvest study, El-Lattief (2011) reported 10.3, 13.9, and 17.5 tillers per plant before each harvest, respectively. Maximum tillering in 2016 and 2017 did not reach above 7.5 tillers per plant.

At the beginning of the season, the leaf:stem ratio averaged 2.7 and 3.4 across years for forage sorghum and pearl millet, respectively. After a harvest, both crops recovered back to the 90 d harvest interval leaf:stem ratio. The leaf:stem ratio at the end of the season for both years and crops ended around 0.5 (Figures 9 & 10). This concurs with Amodu et al. (2001) that found pearl millet leaf:stem ratio across all accessions and growth stages to be 0.5. This is supported by Bishnoi et al. (1993) that found leaf:stem ratios of pearl millet, sudangrass, and forage sorghum to be 0.6, 0.43, and 0.47, respectively. This differs from Rostamza et al. (2011) that reported an average leaf:stem ratio of 2.0.

In both years after a harvest, pearl millet had higher LAI and PAR than forage sorghum. This can be attributed to at 300 GDDs, forage sorghum produced 69 and 80% of pearl millet leaf:stem ratios in 2016 and 2017, respectively; and forage sorghum produced 39% of pearl millet tillers per plant at 550 GDDs. Because pearl millet had higher values in all four of these attributes, the crop was better able to reduce soil moisture evaporative losses resulting in a higher WUE.

Water Use Efficiency

In 2017, water use efficiency (WUE) was evaluated (Table 3). Pearl millet had a higher WUE in the 45 and 90 d treatments, 30, 45, and 90, WUE was 10.9, 11.8, and 25.8 kg DM ha^{-1} mm^{-1} when compared to forage sorghum, 10.2, 9.5, and 16.4 kg DM ha^{-1}

mm^{-1}, respectively (Figure 11). This concurs with Singh and Singh (1995) that found pearl millet to have a higher WUE than sorghum, 17.9 and 14.4 kg DM ha^{-1} mm^{-1}, respectively. Lower WUE in the 30 and 45 d harvests, across both crops, can be attributed to loss of the crop canopy, increasing evaporation, during a harvest event.

Conclusions

While the maximum amount of forage was produced in the single, 90 d harvest for both crops, it was concluded that rapid growth occurred between 30 and 60 days after emergence. Forage sorghum did out-yield pearl millet; however, pearl millet still may be a viable option for producers in the region. As the crop matured, forage quality decreased and forage DM production increased; however, some forage quality attributes can be retained with more frequent harvests.

A 90 d harvest regime will maximize forage DM production. However, if higher forage quality is desired, shorter cutting intervals are recommended. Frequent harvests reduce DM production potential while retaining high quality potential. Both forage sorghum and pearl millet, after a harvest, responded well early in the season by developing taller plants and achieving full LAI and PAR potential, but accumulated more tillers after a second harvest. When water is a limiting factor, a pearl millet, 90 d harvest interval, production system is desired when comparing WUE between forage sorghum and pearl millet. Further research needs to be understand pearl millet crop establishment and production for the Texas High Plains.

Tables and Figures

Table 1. Average monthly air temperature and total rainfall near Canyon, TX for 2016-2017. Thirty year averages (30-yr) were calculated from data collected from the National Weather Service Forecast Office from 1985-2015.

	Air temperature			Rainfall		
Month	2016†	2017‡	30-yr	2016	2017†	30-yr
		C°			mm	
May	17.3	17.8	19.8	34	40	69
June	25.2	24.2	24.7	26	104	73
July	28.1	25.3	26.3	58	80	58
August	18.6	22.2	25.5	81	128	79
September	15.3	21.2	21.4	40	85	61

† 2016 weather data collected from the National Weather Service Forecast Office (Amarillo, TX) for Canyon, TX.

‡ 2017 weather data collected from onsite weather station (Campbell Scientific, Logan, UT) 100 m from the experimental site.

Table 2. Forage sorghum and pearl millet dry matter (DM) and forage quality means for CP, ADF, NDF, TDN, and RFV near Canyon, TX, in 2016 and 2017.

			2016						2017					
Interval	Crop	Harvest	DM	CP	ADF	NDF	TDN	RFV	DM	CP	ADF	NDF	TDN	RFV
			Mg ha⁻¹	%				RFV	Mg ha⁻¹	%				RFV
30 day	Forage Sorghum	H_{30}	1.06*b*	11	34.7*b*	62.1*a*	63.5*a*	92.8	1.83*b*	10.6*a*	35.8*c*	58.3*a*	62.6*a*	97.3*b*
		H_{60}	3.53*a*	9.2	34.5*b*	60.6*ab*	64.0*a*	95.3	4.09*a*	10.1*ab*	40.2*a*	59.8*a*	57.5*c*	89.5*c*
		H_{90}	0.80*b*	10.5	38.4*a*	57.8*b*	59.5*b*	95.3	0.61*c*	9.4*b*	37.9*b*	53.9*b*	60.2*b*	102.8*a*
		Total	5.38						6.53					
	Pearl Millet	H_{30}	0.50*b*	14.6*a*	30.4*b*	56.5*b*	68.5*a*	107.8*a*	0.88*b*	11.4*a*	34.7*b*	61.2*ab*	63.5*a*	94.3*a*
		H_{60}	2.53*a*	11.0*b*	31.7*b*	58.6*b*	67.4*a*	102.0*a*	4.02*a*	10.5*b*	38.6*a*	63.0*a*	59.7*b*	87.0*b*
		H_{90}	0.93*b*	9.1*b*	37.7*a*	60.6*a*	60.4*b*	91.5*b*	1.09*b*	8.0*c*	39.0*a*	59.4*b*	59.0*b*	91.8*a*
		Total	3.96						5.99					
		SE	0.239	0.83	0.89	1.16	1.01	2.94	0.224	0.27	0.46	0.67	0.47	1.46
45 day	Forage Sorghum	H_{45}	2.65	5.8*b*	38.9*b*	63.9	59.0*a*	85.3*b*	4.59*a*	9.9*a*	38.9	62.1*a*	59	87.8*b*
		H_{90}	2.34	6.5*a*	39.9*a*	62.1	57.9*b*	86.5*a*	2.46*b*	6.7*b*	38.2	57.2*b*	59.9	96.3*a*
		Total	4.99						7.05					
	Pearl Millet	H_{45}	1.57	14.8*a*	32.5*b*	60.4*b*	66.0*a*	98.0*a*	2.78	12.7*a*	36.8*b*	63.8*a*	61.5*a*	87.8
		H_{90}	2.24	12.0*b*	35.9*a*	61.5*a*	62.6*b*	92.5*b*	2.86	6.0*b*	38.8*a*	60.3*b*	59.0*b*	90.5
		Total	3.81						5.64					
		SE	0.271	0.62	0.62	0.7	0.68	1.65	0.225	0.38	0.46	0.59	0.55	1.3
90 day	Forage Sorghum	H_{90}	11.05*A*	4.4	38.6	62	59.5	88.5	15.51*A*	4.2	39.9	58.3*B*	57.9	92.5
	Pearl Millet	H_{90}	6.29*B*	5.1	38	64.5	59.9	85.5	9.87*B*	4.3	39.3	59.8*A*	58.6	90.8
		SE	1.306	0.43	0.97	1.03	1.12	2.64	0.429	0.3	0.22	0.4	0.3	0.69

† Columns with same lowercase letter are not different between harvests within harvest interval, within crop, within year.

‡ Columns with same uppercase letter are not different between harvests within harvest interval, between crops, within year.

§ $\alpha<0.05$.

Table 3. Water use efficiency, dry matter (DM), and total water use means of forage sorghum and pearl millet under three different harvest intervals near Canyon, TX in 2017.

Crop	Interval	Dry Matter	Total Water Used	Water Use Efficiency
		kg ha^{-1}	mm	kg ha^{-1} mm^{-1}
Forage Sorghum	30	6528*bA*	599	10.15*bA*
	45	7051*bA*	596	9.54*bB*
	90	15513*aA*	602	16.43*aB*
Pearl Millet	30	5996*bA*	591	10.91*bA*
	45	5637*bB*	591	11.83*bA*
	90	9873*aB*	601	25.77*aA*
	SE	417.8	2.2	0.701

† Columns with same lowercase letter are not different between harvest intervals within crop.

‡ Columns with same uppercase letter are not different between crops within harvest interval.

§ $\alpha<0.05$.

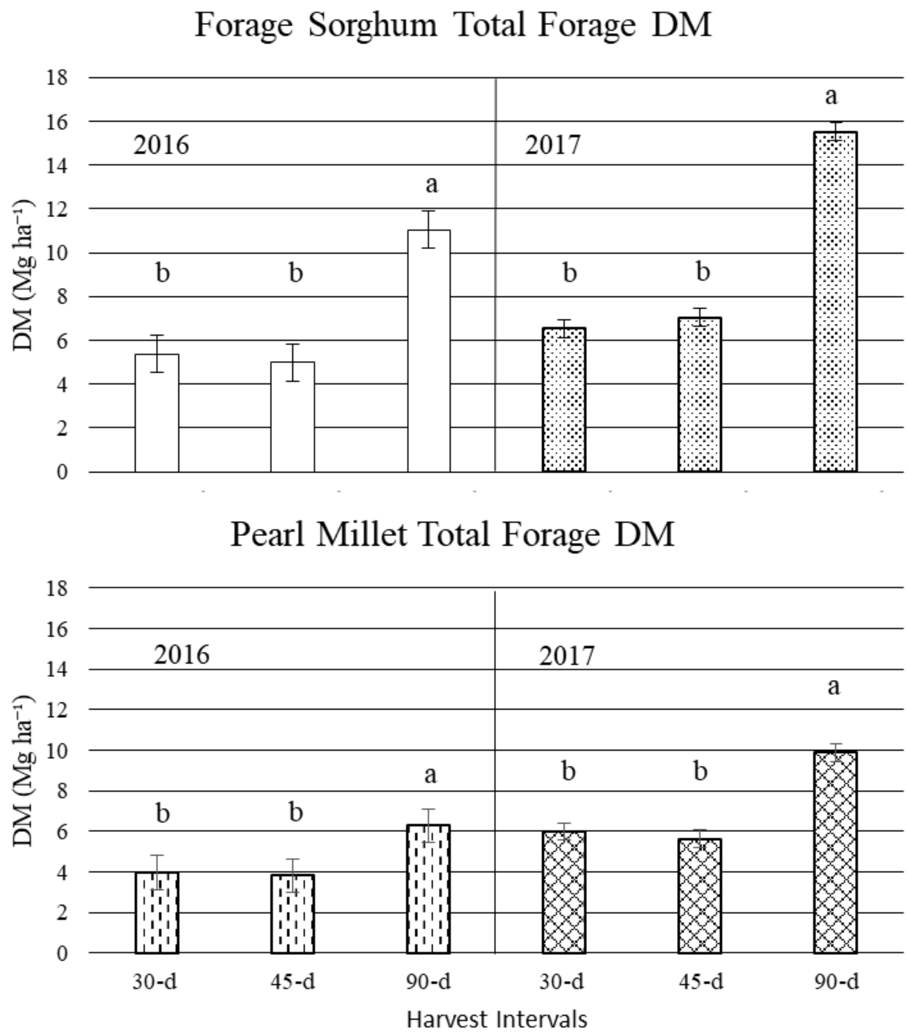


Figure 1. Total forage sorghum and pearl millet dry matter (DM) means near Canyon, TX in 2016 and 2017.
† The same lowercase letter represents similar means within year, within crop.
‡ $\alpha<0.1$.

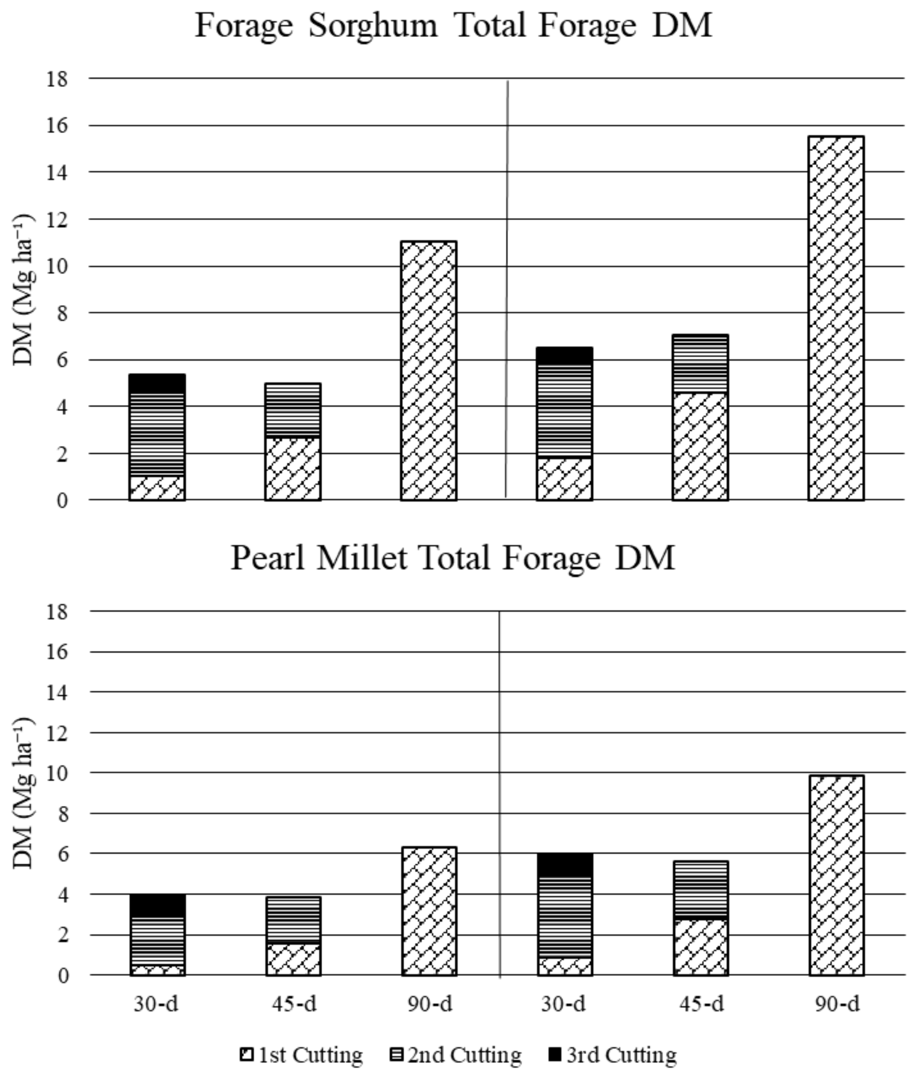
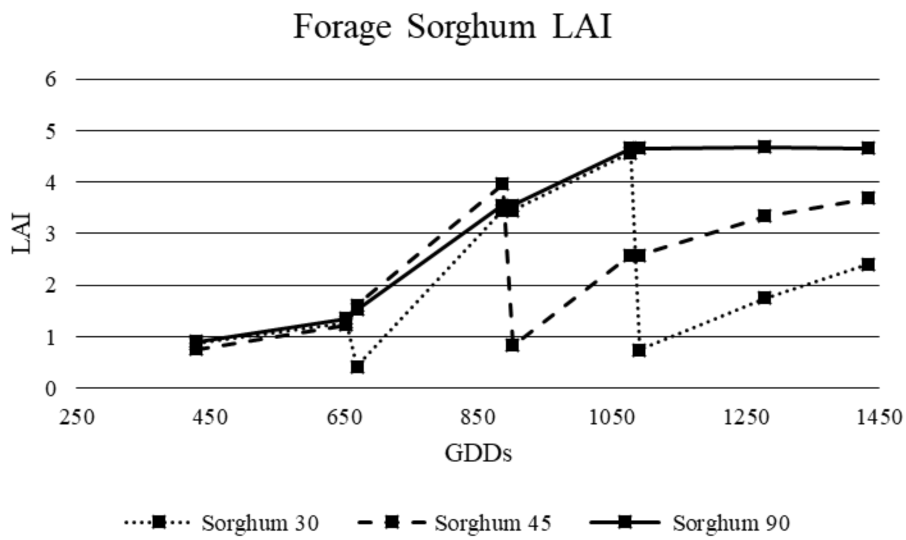


Figure 2. Total accumulated forage sorghum and pearl millet dry matter (DM) means near Canyon, TX in 2016 and 2017.



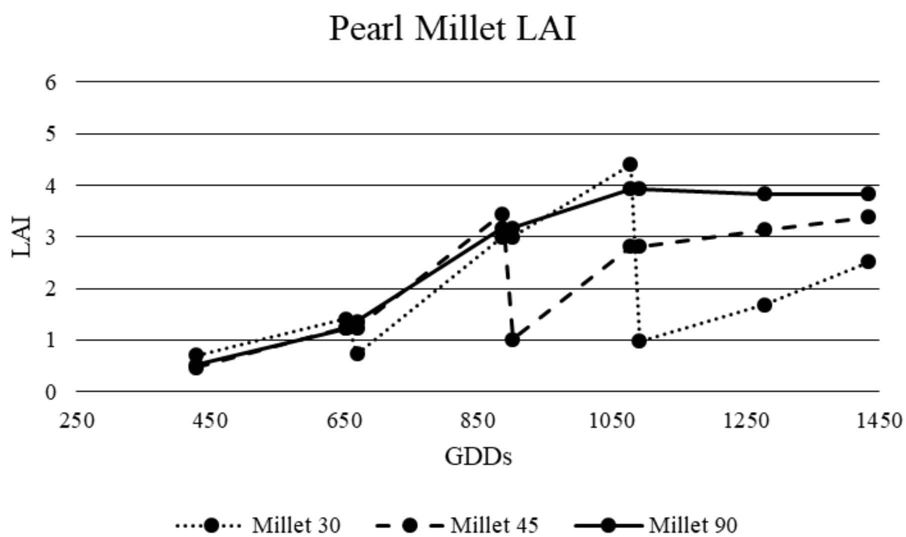
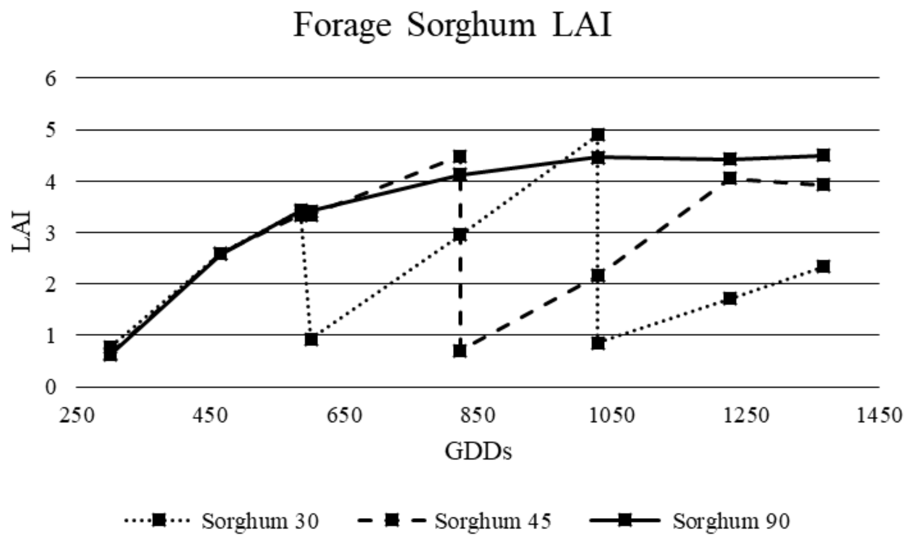


Figure 3. Forage sorghum and pearl millet leaf area index (LAI) means for 2016 near Canyon, TX.



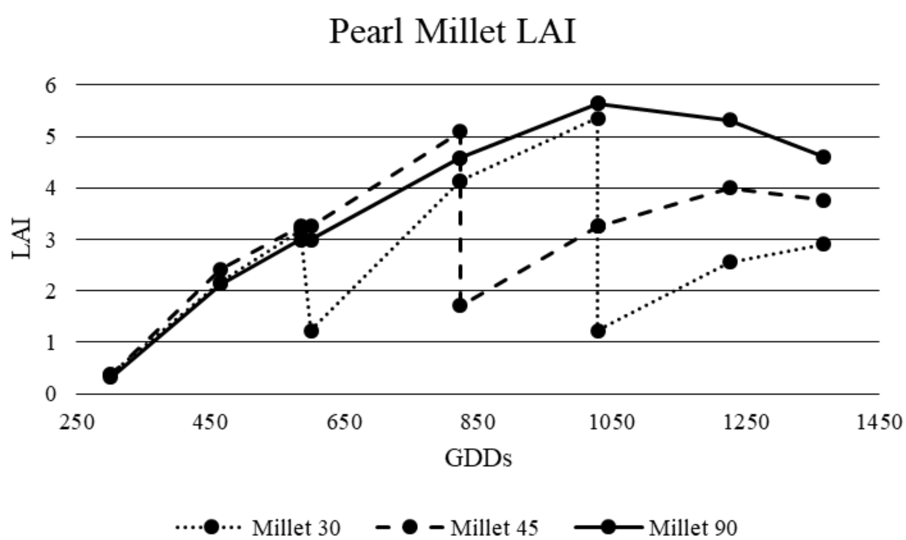


Figure 4. Forage sorghum and pearl millet leaf area index (LAI) means for 2017 near Canyon, TX.

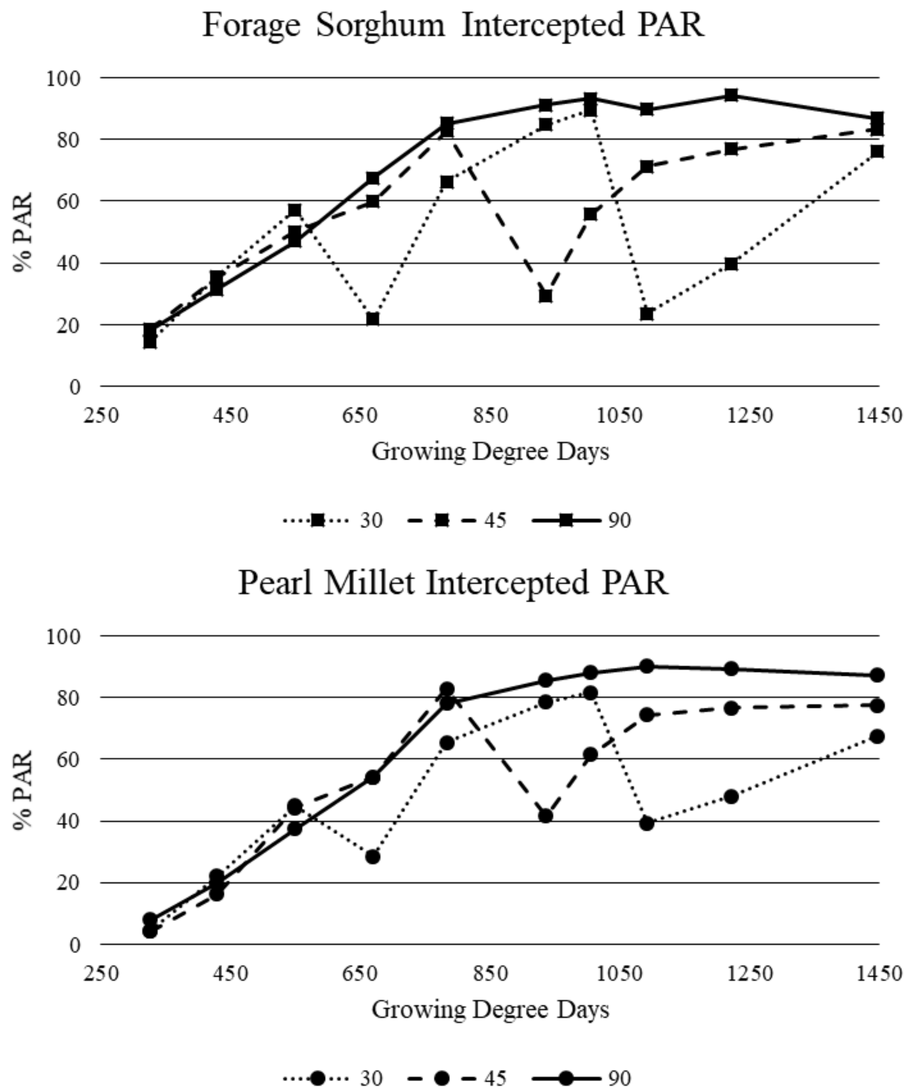
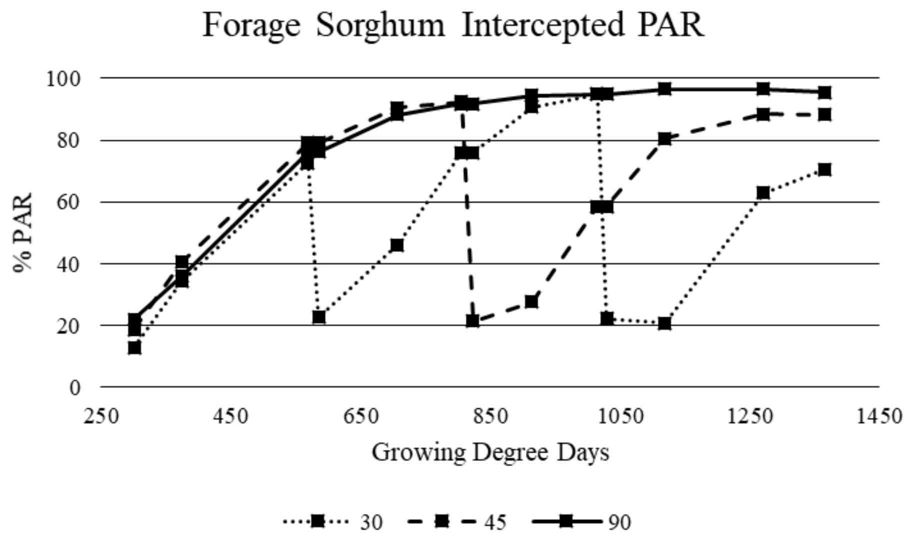


Figure 5. Forage sorghum and pearl millet intercepted photosynthetically active radiation (PAR) means for 2016 near Canyon, TX.



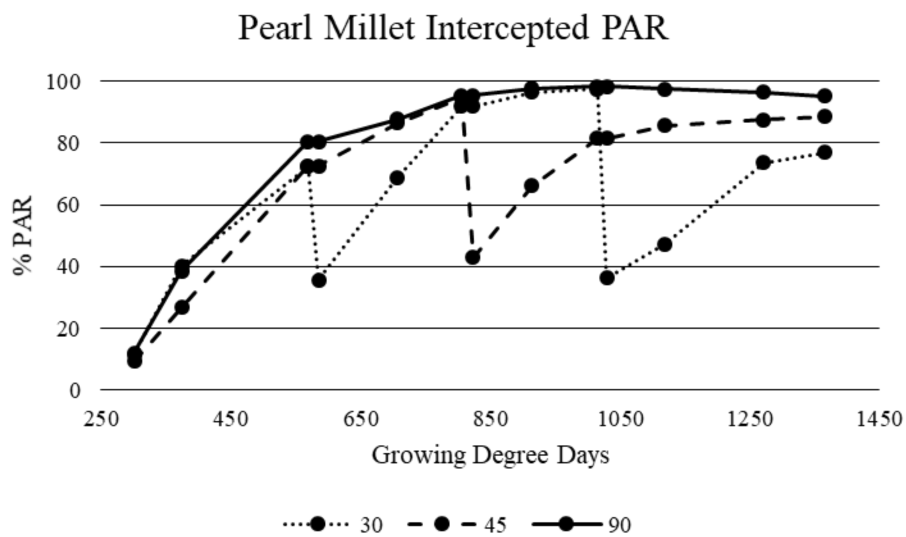
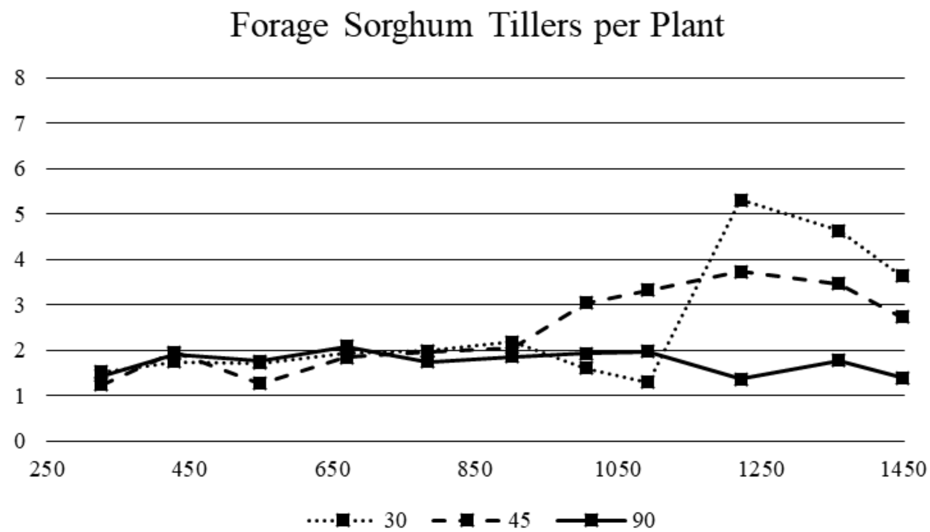


Figure 6. Forage sorghum and pearl millet intercepted photosynthetically active radiation (PAR) means for 2017 near Canyon, TX.



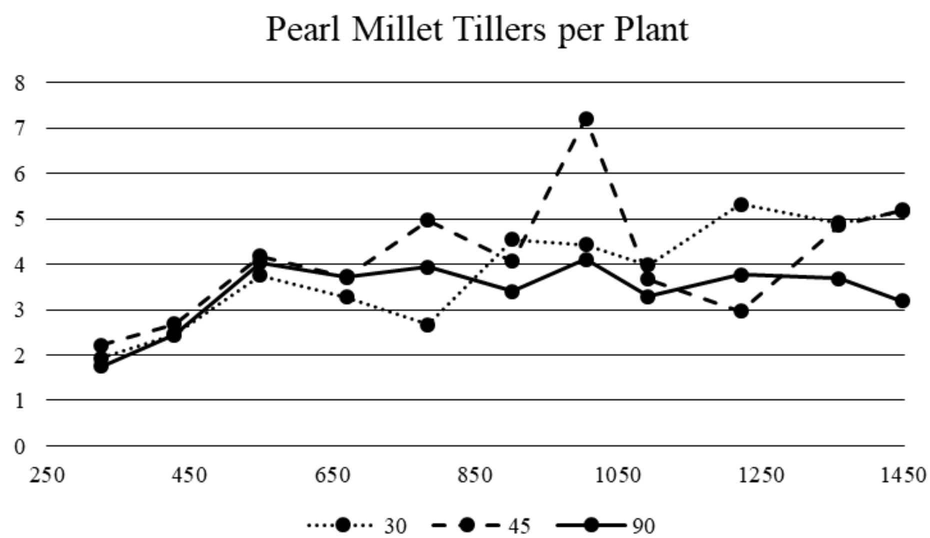


Figure 7. Forage sorghum and pearl millet tillers per plant means for 2016 near Canyon, TX.

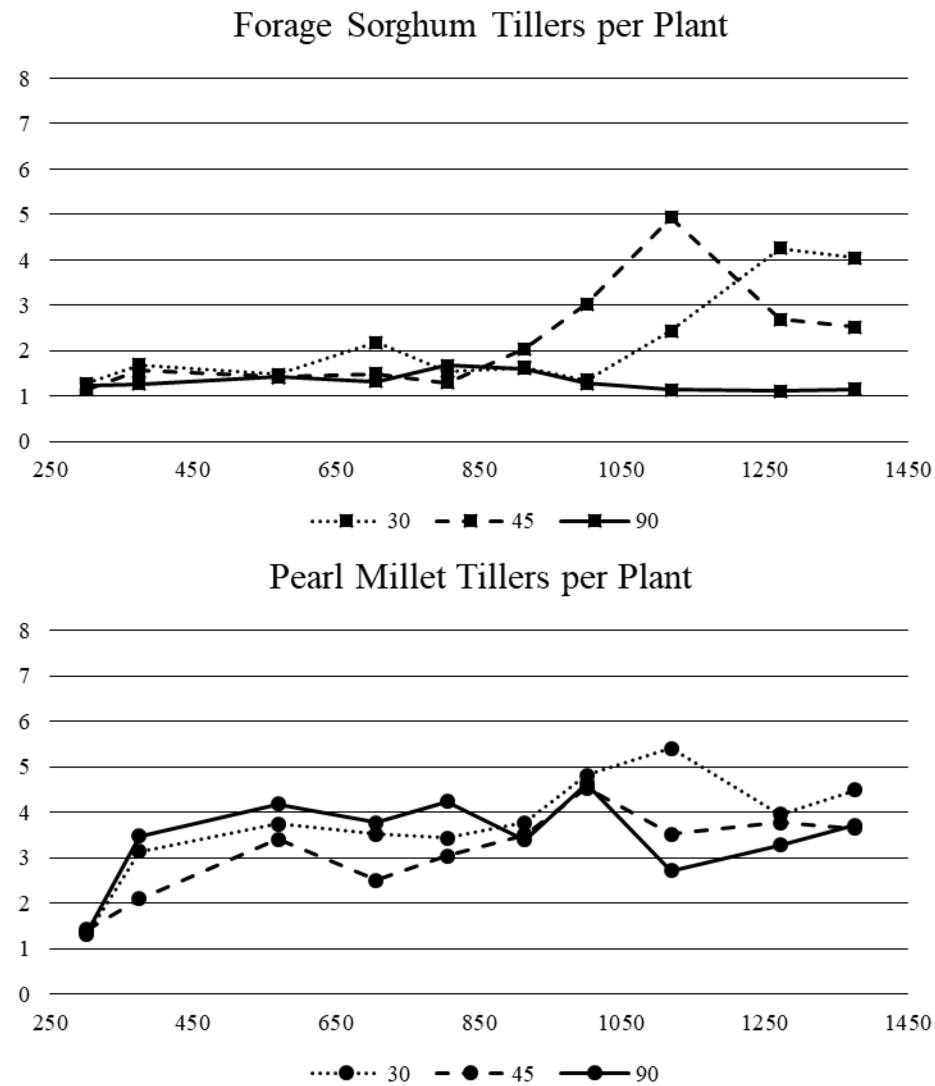


Figure 8. Forage sorghum and pearl millet tillers per plant means for 2016 near Canyon, TX.

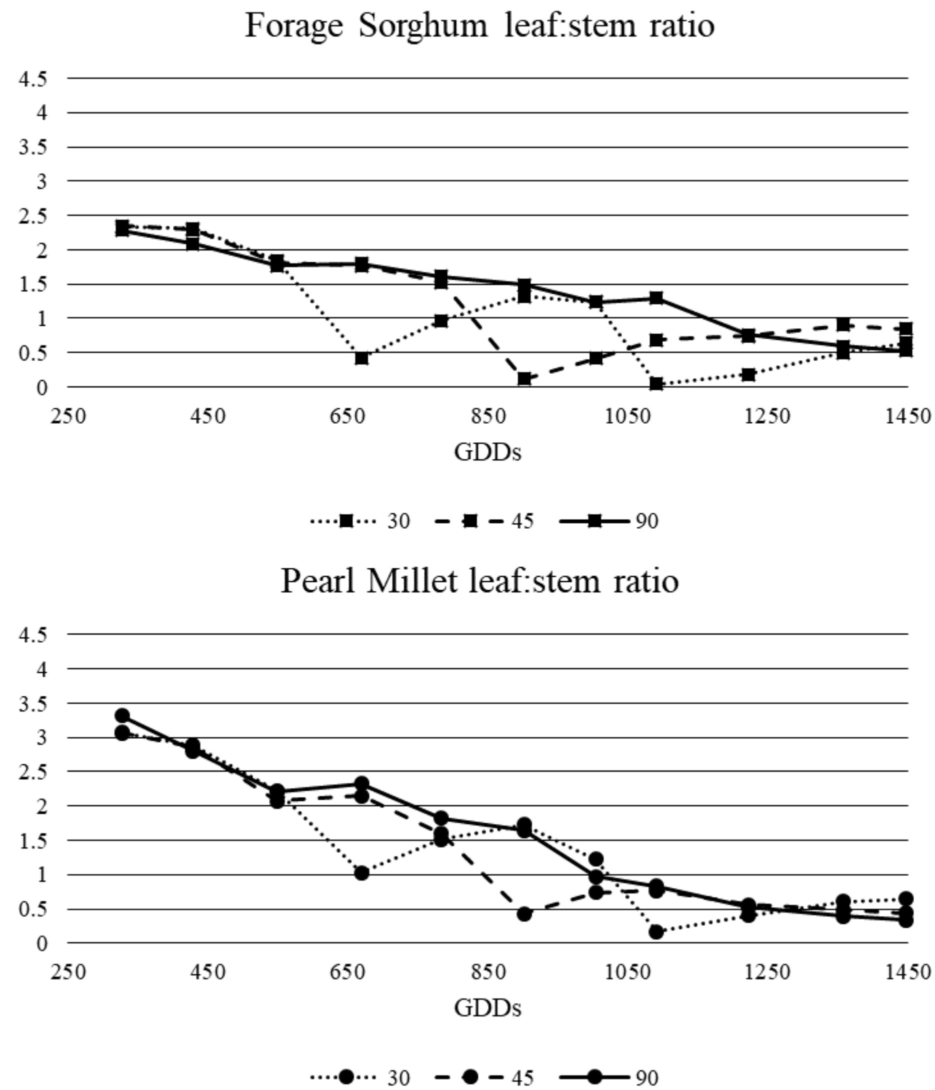
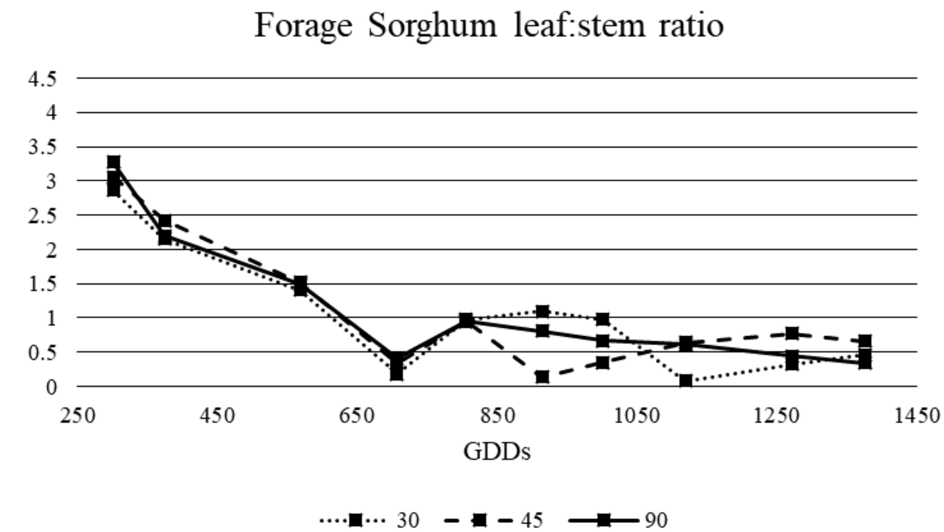


Figure 9. Forage sorghum and pearl millet leaf:stem ratio means for 2016 near Canyon, TX.



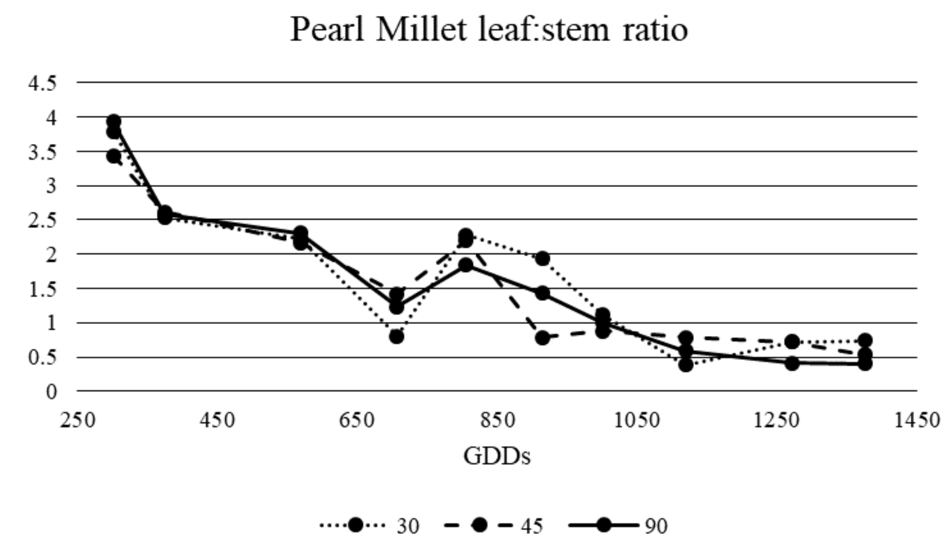


Figure 10. Forage sorghum and pearl millet leaf:stem ratio means for 2017 near Canyon, TX.

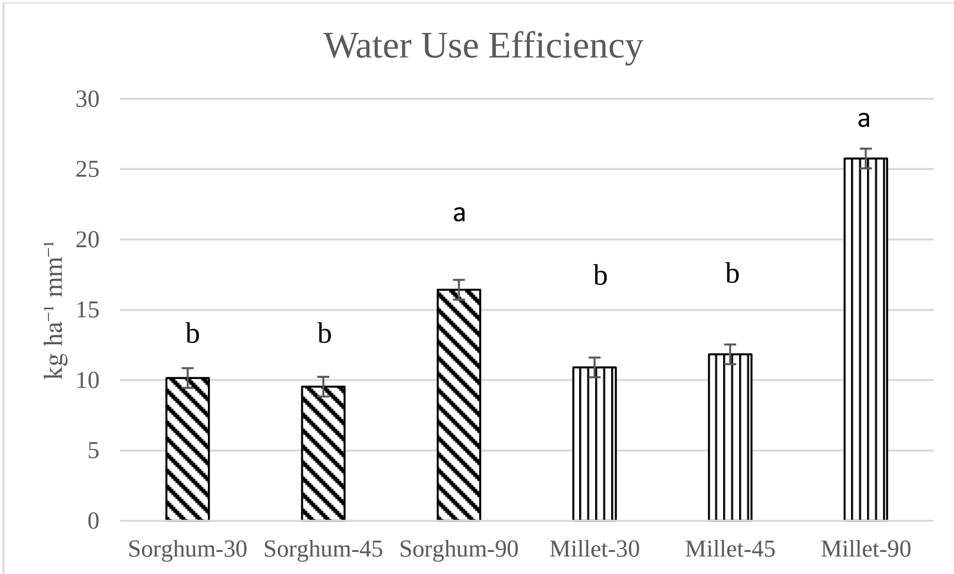


Figure 11. Water use efficiency means near Canyon, TX in 2017.
† The same lowercase letter are not different within crop.
‡ α<0.05.

LITERATURE CITED

Alagarswamy, G., & Ritchie, J. T. (1991). Phasic development in CERES-Sorghum model, in: T. Hodges (Ed.), *Predicting crop phenology*, 143-152.

Amodu, J. T., Kallah, M. S., Onifade, O. S., Omokanye, A. T., & Adeyinka, I. A. (2001). The effect of harvesting at different growth stages on yield and quality of three late-maturing pearl millet accessions in northern Nigeria. *Tropical Grasslands, 35*(3), 175-179.

Ankom. 2006. Ankom Technology Method 5. Acid Detergent Fiber in Feeds. Filter Bag Technique. Ankom Technology. Macedon, New York. This method is a modification of AOAC Official Method 973.18. Fiber (Acid Detergent) and Lignin (H2SO4) in Animal Feed. Official Methods of Analysis of AOAC International. 19th ed. Dr. George W. Latimer, Jr (ed). Gaithersburg, Maryland.

Ankom. 2006. Ankom Technology Method 6. Neutral Detergent Fiber in Feeds. Filter Bag Technique. Ankom Technology. Macedon, New York. This method is a modification of 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, Maryland.

AOAC International. 2012. AOAC Method 990.03. Protein (Crude) in Animal Feed. Combustion Method. Official Methods of Analysis of AOAC International. 19th ed. George W. Latimer, Jr (ed). Gaithersburg, Maryland.

Ball, C. R. 1903. Pearl Millet. *USDA Farmers' Bull*. 168.

Bishnoi, U. R., Oka, G. M. and Fearon, A. L. (1993). Quantity and quality of forage and silage of pearl millet in comparison to Sudax, grain, and forage sorghum harvested at different growth stages. Journal of Tropical Agriculture (Trinidad), 70, 98–102.

Burger, A. W., & Hittle, C. N. (1967). Yield, protein, nitrate, and prussic acid content of sudangrass, sudangrass hybrids, and pearl millets harvested at two cutting frequencies and two stubble heights. *Agronomy Journal*, *59*(3), 259-262.

Cherney, D. J., Patterson, J. A., & Johnson, K. D. (1990). Digestibility and feeding value of pearl millet as influenced by the brown-midrib, low-lignin trait. *Journal of animal science, 68*(12), 4345-4351.

Clapp, J. G., & Chamblee, D. S. (1970). Influence of different defoliation systems on the regrowth of pearl millet, hybrid sudangrass, and two sorghum-sudangrass hybrids from terminal, axillary, and basal buds. *Crop science*, *10*(4), 345-349.

Duncan, R. R., & Gardner, W. A. (1984). The influence of ratoon cropping on sweet sorghum yield, sugar production, and insect damage. *Canadian Journal of Plant Science*, *64*(2), 261-274.

El-Lattief, E. A. (2011). Growth and fodder yield of forage pearl millet in newly cultivated land as affected by date of planting and integrated use of mineral and organic fertilizers. *Asian Journal of Crop Science*, *3*(1), 35-42.

Fageria, N. K., Baligar, V. C., & Clark, R. (2006). *Physiology of crop production*. CRC Press.

Hanna W. W., Baltensperger D. D., Seetharam A. (2004). Pearl millet and other millets. WI: American Society of Agronomy 537–560.

Harlan, J. R., & de Wet, J. M. (1971). Toward a rational classification of cultivated plants. *Taxon*, 509-517.

Hill, G. M., Hanna, W. W., & Gates, R. N. (1999). Pearl millet cultivar and seeding method effects on forage quality and performance of grazing beef heifers. *Journal of production agriculture*, *12*(4), 578-580.

Maman, N., Mason, S. C., Galusha, T., & Clegg, M. D. (1999). Hybrid and nitrogen influence on pearl millet production in Nebraska: yield, growth, and nitrogen uptake, and nitrogen use efficiency. *Agronomy Journal*, *91*(5), 737-743.

Marsalis, M. 2011. Sorghum Forage Production in New Mexico. New Mexico State Coop. Ext. Serv. A-332.

Marsalis, M. A., Lauriault, L. M., & Trostle, C. (2012). Millets for forage and grain in New Mexico and west Texas.

Marshall, B., & Willey, R. W. (1983). Radiation interception and growth in an intercrop of pearl millet/groundnut. *Field Crops Research*, *7*, 141-160.

Maughan, M., Voigt, T., Parrish, A., Bollero, G., Rooney, W., & Lee, D. K. (2012). Forage and energy sorghum responses to nitrogen fertilization in central and southern Illinois. *Agronomy journal*, *104*(4), 1032-1040.

Mays, D. A., & Washko, J. B. (1962). Refractometric Determination of "Sucrose Equivalent" Levels in the Stubble of Sudangrass and Pearl Millet1. *Crop Science*, *2*(1), 81-82.

McCormick, M. E., Morris, M. E., Ackerson, B. A., & Blouin, D. C. (1995). Ratoon cropping forage sorghum for silage: yield, fermentation, and nutrition. *Agronomy Journal*, *87*(5), 952-957.

Nasiev, B. N. (2013). Selection of high-yielding agrophytocenoses of annual crops for fodder lands of frontier zone. *Life Science Journal*, *10*(11), 267-271.

National Weather Service Forcast Office. (n.d.). Retrieved March 8, 2018, from http://w2.weather.gov/climate/xmacis.php?wfo=ama

Oliver, A. L., Pedersen, J. F., Grant, R. J., & Klopfenstein, T. J. (2005). Comparative Effects of the Sorghum-6 and-12 Genes: I. Forage Sorghum Yield and Quality. *Crop science*, *45*(6), 2234-2239.

Pedersen, J. F., & Rooney, W. L. (2004). Sorghums. *Warm-Season (C4) Grasses*, (warmseasonc4gra), 1057-1079.

Porter, K., Colenbrander, V., Lechtenberg, V., & Axtell, J. (1978). Phenotype, fiber composition, and in vitro dry matter disappearance of chemically induced brown midrib (bmr) mutants of sorghum. *Crop Science*, (2), 205-208.

Rachie, K. O., & Majmudar, J. V. (1980). *Pearl millet*. University Park: Pennsylvania State University Press, c1980.

Rostamza, M., Chaichi, M. R., Jahansouz, M. R., & Alimadadi, A. (2011). Forage quality, water use and nitrogen utilization efficiencies of pearl millet (Pennisetum americanum L.) grown under different soil moisture and nitrogen levels. *Agricultural Water Management*, *98*(10), 1607-1614.

Saeed, I. A. M., & El-Nadi, A. H. (1998). Forage sorghum yield and water use efficiency under variable irrigation. *Irrigation science*, *18*(2), 67-71.

Sanderson, M.A., G. Ali, M.A. Hussey, and F.R. Miller. (1995). Forage quality and agronomic traits of sorghum-sudangrass hybrids. Texas Agric. Exp. Stn. MP-1765. College Station.

Sattler, S. E., Funnell-Harris, D. L., & Pedersen, J. F. (2010). Brown midrib mutations and their importance to the utilization of maize, sorghum, and pearl millet lignocellulosic tissues. *Plant Science*, *178*(3), 229-238.

Shashikala, T., Rai, K. N., Balaji Naik, R., Shanti, M., Chandrika, V., & Loka Reddy, K. (2013). Fodder potential of multicut pearl millet genotypes during summer season. *International journal of Bio-resource and Stress Management*, *4*(4), 628-630.

Singh, B. R., & Singh, D. P. (1995). Agronomic and physiological responses of sorghum, maize and pearl millet to irrigation. *Field Crops Research*, *42*(2), 57-67.

Smith, C. W., & Frederiksen, R. A. (Eds.). (2000). *Sorghum: Origin, history, technology, and production* (Vol. 2). John Wiley & Sons.

Staggenborg, S. 2016. Forage and Renewable Sorghum End Uses. Sorghum: State of the Art and Future Perspectives, Ignacio Ciampitti and Vara Prasad, editors. Agronomy Monograph 58.

Stephenson, R.J., and G.L. Posler. 1984. Forage Yield and Regrowth of Pearl Millet. Trans. Kansas Acad. Sci. (1903-). Vol. 87: 91-97.

Unger, P. W. (1988). Grain and forage sorghum production with no-tillage on dryland. *Agronomy journal*, *80*(2), 193-197.

Venuto, B., & Kindiger, B. (2008). Forage and biomass feedstock production from hybrid forage sorghum and sorghum–sudangrass hybrids. *Grassland science*, *54*(4), 189-196.

Virmani, S. M., Tandon, H. L. S., & Alagarswamy, G. (1989). *Modeling the growth and development of sorghum and pearl millet*. International Crops Research Institute for the Semi-Arid Tropics.

APPENDIX

Supplementary Table 1. Forage sorghum and pearl millet forage quality means for CP, ADF, NDF, TDN, energy, and RFV near Canyon, TX in 2016.

Interval	Crop	Harvest	CP	ADF	NDF	TDN	Net Energy, Maint	Net Energy, Gain	Net Energy, Lact	Digestible Energy	Met. Energy, Beef	RFV
			%				Mcal/lb					
30	S†	H_{30}	11.0	34.7	62.1	63.5	0.648	0.383	0.653	1.275	1.040	92.8
		H_{60}	9.2	34.5	60.6	64.0	0.653	0.390	0.658	1.280	1.050	95.3
		H_{90}	10.5	38.4	57.8	59.5	0.585	0.328	0.608	1.190	0.978	95.3
	M‡	H_{30}	14.6	30.4	56.5	68.5	0.720	0.448	0.708	1.370	1.123	107.8
		H_{60}	11.0	31.7	58.6	67.4	0.705	0.433	0.695	1.348	1.105	102.0
		H_{90}	9.1	37.7	60.6	60.4	0.603	0.340	0.618	1.213	0.993	91.5
45	S	H_{45}	12.0	35.9	61.5	62.6	0.635	0.373	0.643	1.255	1.028	92.5
		H_{90}	6.5	40.0	62.1	57.9	0.563	0.308	0.590	1.160	0.950	86.5
	M	H_{45}	14.8	32.5	60.4	66.0	0.685	0.418	0.680	1.323	1.083	98.0
		H_{90}	5.8	38.9	63.9	59.0	0.578	0.323	0.603	1.183	0.970	85.3
90	S	H_{90}	4.4	38.6	62.0	59.5	0.588	0.328	0.608	1.190	0.978	88.5
	M	H_{90}	5.1	38.0	64.5	59.9	0.590	0.333	0.613	1.198	0.988	85.5

† S = forage sorghum

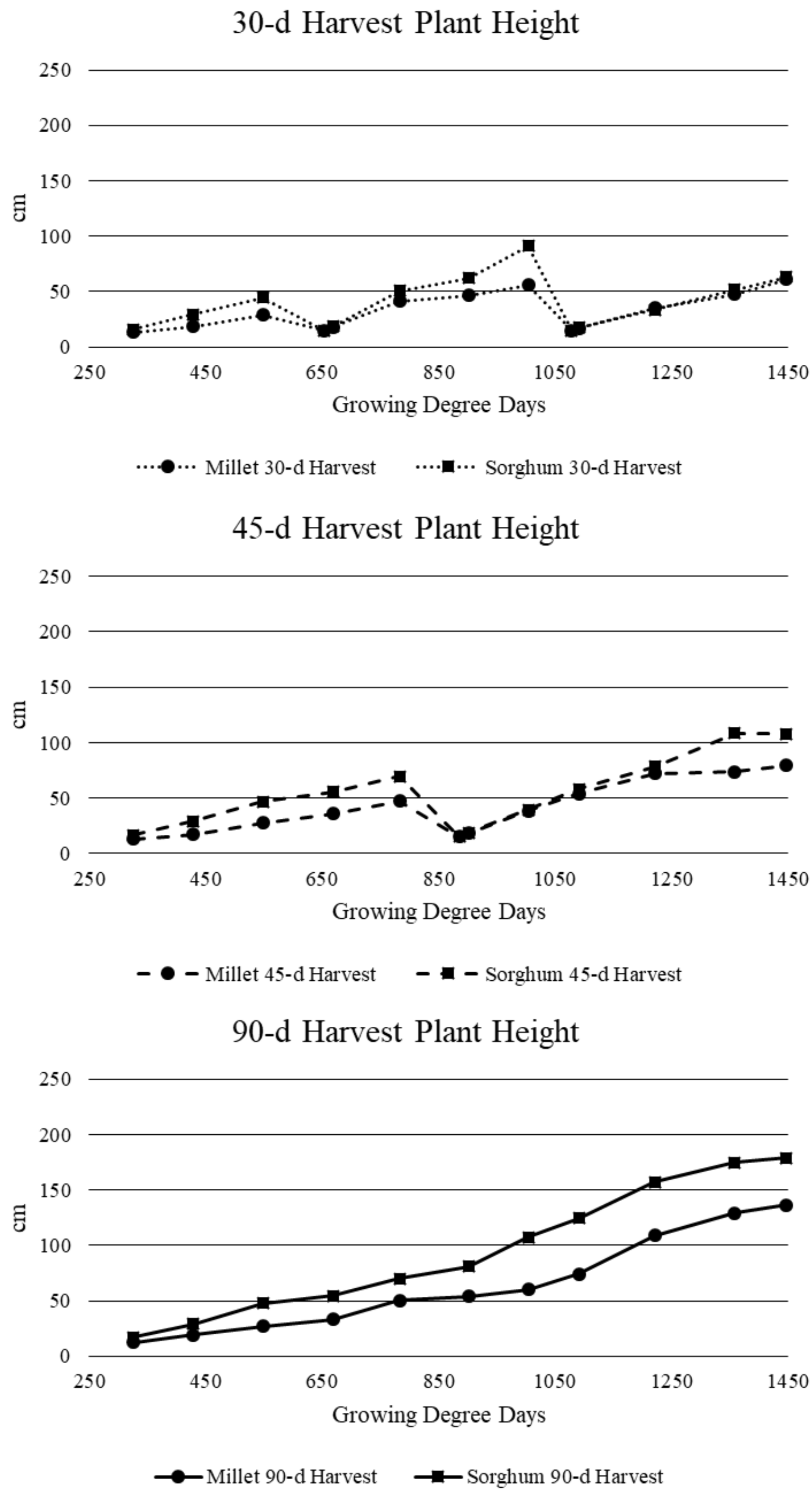
‡ M = pearl millet

Supplementary Table 2. Forage sorghum and pearl millet forage quality means for CP, ADF, NDF, TDN, energy, and RFV near Canyon, TX in 2017.

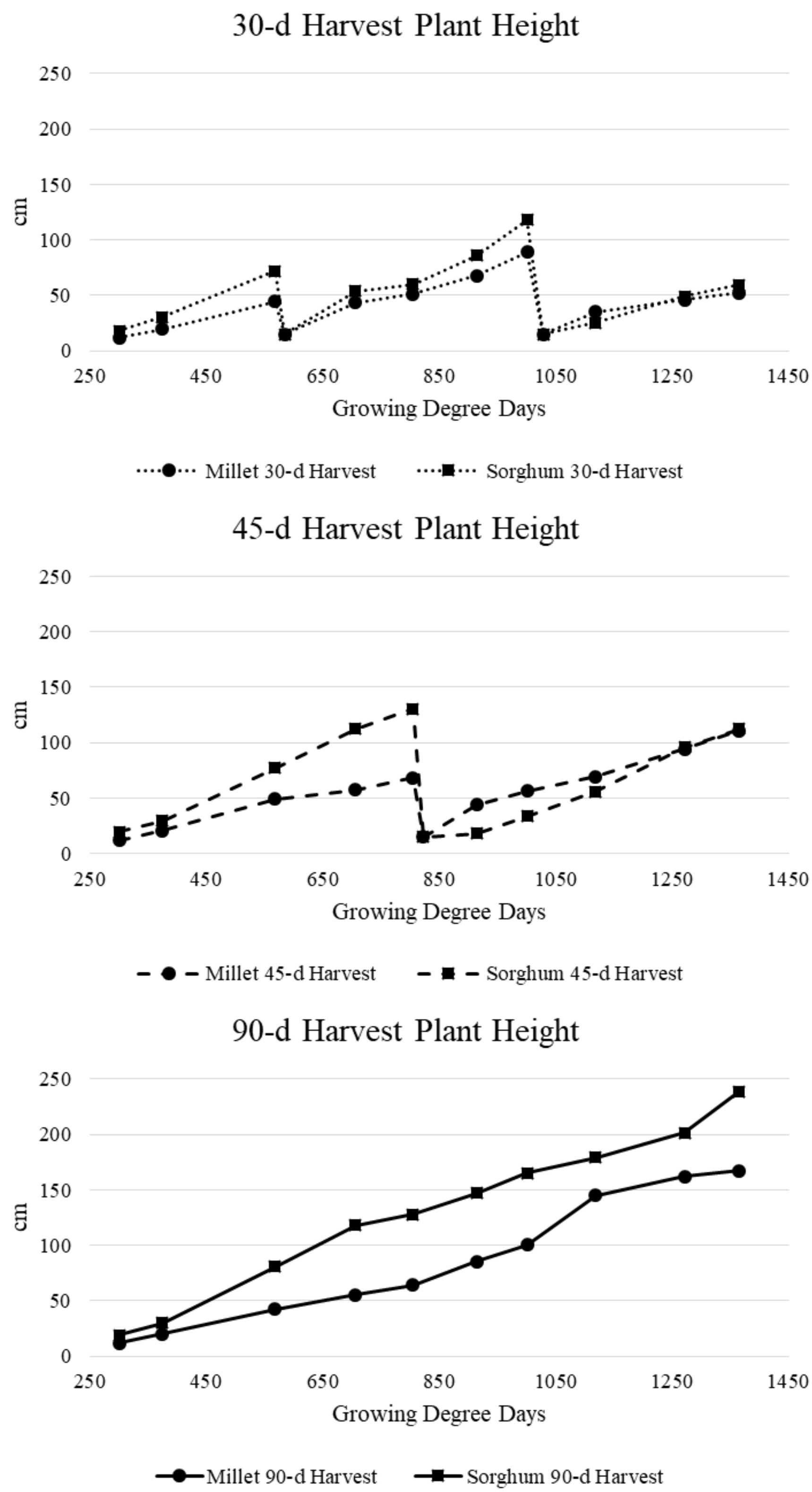
Interval	Crop	Harvest	CP	ADF	NDF	TDN	Net Energy, Maint	Net Energy, Gain	Net Energy, Lact	Digestible Energy	Met. Energy, Beef	RFV
			%				Mcal/lb					
30	S†	H_{30}	10.6	35.8	58.3	62.6	0.633	0.373	0.643	1.255	1.028	97.3
		H_{60}	10.1	40.2	59.8	57.5	0.558	0.300	0.585	1.150	0.945	89.5
		H_{90}	9.4	37.9	53.9	60.2	0.595	0.335	0.615	1.203	0.993	102.8
	M‡	H_{30}	11.4	34.7	61.2	63.5	0.650	0.383	0.653	1.275	1.040	94.3
		H_{60}	10.5	38.6	63.0	59.7	0.590	0.330	0.610	1.198	0.983	87.0
		H_{90}	8.0	39.0	59.4	59.0	0.583	0.323	0.603	1.185	0.973	91.8
45	S	H_{45}	9.9	38.9	62.1	59.0	0.580	0.323	0.603	1.185	0.970	87.8
		H_{90}	6.7	38.2	57.2	59.9	0.595	0.335	0.613	1.203	0.985	96.3
	M	H_{45}	12.7	36.8	63.8	61.5	0.618	0.358	0.630	1.233	1.008	87.8
		H_{90}	6.0	38.8	60.3	59.0	0.580	0.323	0.603	1.183	0.973	90.5
90	S	H_{90}	4.2	39.9	58.3	57.9	0.563	0.308	0.590	1.160	0.953	92.5
	M	H_{90}	4.3	39.3	59.8	58.6	0.575	0.318	0.598	1.175	0.965	90.8

† S = forage sorghum

‡ M = pearl millet



Supplementary Figure 1. Pearl millet and forage sorghum 30, 45, and 90 d plant height means in 2016.



Supplementary Figure 2. Pearl millet and forage sorghum 30, 45, and 90 d plant height means in 2017.