Evaluating Forage Sorghum-Cowpea and Pearl Millet-Cowpea Production and Quality in the Texas High Plains

by

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A Thesis Submitted in Partial Fulfillment

of the Requirements for the Degree

MASTER OF SCIENCE

Major Subject: Plant, Soil, and Environmental Science

West Texas A&M University

Canyon, Texas

May 2022

ABSTRACT

Despite declining water availability in the semi-arid southern High Plains, demand for high-quality forages by the livestock and dairy industries continues to grow. Alternative forage crops with high water use efficiencies should be explored to meet this demand. Grass-legume intercrops may improve the nutritive value of the forage product, but viable intercrops must maintain yield levels. The purpose of this study was to evaluate forage sorghum [*Sorghum bicolor* (L.) Moench]-cowpea [*Vigna unguiculate* (L.) Walp] and pearl millet [*Pennisetum glaucum* (L.) Leeke]-cowpea intercrops for forage production and quality. Four planting arrangements per grass species were included in the 2020 and 2021 growing seasons to evaluate forage production of sorghum-cowpea and pearl millet-cowpea intercrops under limited irrigation. Treatments were sole pearl millet, sole forage sorghum, sole cowpea, or mixtures of either pearl millet-cowpea or forage sorghum-cowpea planted in the same row, alternating rows (millet-cowpea 1:1 or sorghum-cowpea 1:1), or two rows alternating (millet-cowpea 2:2 or sorghum-cowpea 2:2). Intercrop biomass yields ranged from 11.6 to 16.2 Mg ha^{-1} in 2020 and from 7.2 to 12.4 Mg ha^{-1} in 2021. Results from both study years indicate that the studied intercrops are able to maintain yield, quality, and WUE levels similar to sole pearl millet and forage sorghum.

AKNOWLEDGEMENTS

When I came to Canyon as a scared little sophomore, I could not have imagined how great being a Buff would be. The Ag Department has pushed me to be better and think bigger while providing the guidance and resources to do so. Throughout the last six years in Canyon, I have received an immense amount of support and assistance. First, I would like to thank Dr. Blaser, Dr. Darapuneni, and Dr. Rhoades for serving on my committee.

Dr. Blaser’s door was always open when I needed guidance about research or life. He steered me in the right direction when I needed it but allowed this paper to be my own work. I deeply appreciate Dr. Blaser for giving me the opportunity to conduct this research under an assistantship. He has patiently led me through the process of learning to conduct research and write scientifically. Whether in a crowded school van or in his office, he always had the best advice that I’ll miss hearing every week.

This project would not have been possible without Dr. Darapuneni. I deeply appreciate the opportunity to collaborate with NMSU. Dr. Darapuneni provided valuable guidance along this journey and always had positive feedback to my emails that had too many questions. This project seemed so intimidating when I first read about it, but his support and suggestions helped me break it down into achievable steps.

I know that anytime I ask Dr. Rhoades a question, he will help me find an answer before giving me a new question to ponder. He held me accountable to understanding my study and provided encouragement at a critical point in this journey. His encouragement and service on my committee is so appreciated. Dr. Rhoades still intimidates me but maybe a little less than when I was an undergraduate. His depth of curiosity and knowledge inspires me to push myself after graduation.

Leonard Lauriault provided a great deal of guidance on this project, and I appreciate that he was willing to share his wisdom. The opportunity to work with him and visit the Tucumcari station was a wonderful experience.

I would also like to thank Haley Mosqueda for helping me with my data collection. The fact that we usually had the same questions at the same time made the process of learning how much I didn’t know feel so much less intimidating. I’m so glad we were able to go through this process together and that you’re defending before me. North Dakota is so lucky to have your passion and talent.

I would like to thank Dr. Blaser for allowing me to serve as a Plant Science TA. I had the opportunity to interact with some amazing students from all disciplines. Without the chance to stand in front of a classroom, I doubt I would have the courage to even walk into the room to defend my thesis. While I may have bored a student or thirty, I thank them for giving me the opportunity to share my love of Plant Science and to develop the confidence to communicate it. I know that Kylie Scott is far beyond equipped to carry on that torch and will continue to positively impact the agricultural industry through her successes.

I cannot fully express my thankfulness to the amazing faculty and staff in the WT Department of Agricultural Sciences for instilling qualities that make students successful. Dr. Kieth provides a shining example of what riding for the WT brand looks like. I hope that I can channel even a fraction of his positivity and love for agriculture. During my undergraduate studies, Coach Ellis built up my confidence. She impressed upon me the importance of owning your choices and holding yourself accountable. Dr. Pipkin, Mrs. Jones-Gray, and Dr. Bednarz provided positivity in even the most passing of conversations and demonstrated a passion for their disciplines that I will carry with me.

Graduate school would not have been possible with the love and support of my parents and family. Knowing that I had a whole crowd standing behind me willing to listen to my doubts and celebrate my successes made all the difference. The words of encouragement from my parents will stay with me forever, and I will spend my life trying to match their work ethics. Third graduation is the charm, and they’ll finally get to see me walk the stage! My sister Sarah listened to every story I had, even the boring ones. Our trip to the Grand Tetons will always remind me of us in this stage of life.

While Canyon will always feel like home, that feeling will continue on in the people in my life. Hannah, my roommate, has put up with all of my plant rants and has been an absolute rock. Her support was vital throughout this process, and I cannot imagine how different life would be if I hadn’t stayed at WT for graduate school and met her. I’m beyond grateful that the equestrian team brought Catie into my life. My fellow Okie and broken kid, her enthusiasm and energy are exhausting and inspiring and appreciated all at once. I cannot thank her enough for challenging me to be better. Finally, Cade’s encouragement and support has been unending. Thanks for celebrating the small successes and reminding me that I actually do know things.

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LITERATURE REVIEW

Forage in the Texas Panhandle

Access to local crops is emphasized by dairy producers due to the difficulty of transporting high-moisture silage over long distances (Guerrero et al., 2019). Dairies primarily demand maize silage, but sorghum silage presents a possible alternative that requires up to one-third less water. Almas et al. (2017) identified sorghum silage as an economical alternative to maize silage in the High Plains under current and projected water conditions. Increased production of sorghum silage in the Texas Panhandle from 2000 to 2015 may reflect decreased pumping capacity and increased drought conditions unfavorable to maize production (Guerrero et al., 2019).

Water availability impacts growth, development, and dry matter production of forage crops (Bhattarai et al., 2020a; Fagaria et al., 2006). In comparison to grain crops, the earlier harvest of forage and silage crops lowers required irrigation water. Of the 728,000 hectares planted to sorghum in Texas in 2020, only 40,500 hectares were planted to silage sorghum (USDA-NASS, 2021). Guerrero et al. (2019) reported hectares planted to silage in the Texas High Plains increased by over 4% from 2000 to 2015, indicating regional producers responding to increased silage demand. During the same time period, total irrigated land in the Texas High Plains fell by almost 364,000 hectares, an 18% decrease that follows a long-standing trend in the region.

Water in the Panhandle

Underlying 45.1 million ha^2 and eight states, the Ogallala Aquifer provides a lifeline in the semi-arid Great Plains (Stewart, 2003). The Texas High and Central Plains, notorious for unpredictable weather, face critical groundwater depletion levels (Musick et al., 1990). Irrigation accounts for over 90% of withdrawals from the Ogallala in the Texas High Plains (Colaizzi et al., 2009). Depletion of the Ogallala, high energy prices, and low grain prices are partially responsible for declining hectares of irrigated land in the region. Short-term production goals and long-term groundwater constraints challenge the sustainability of agriculture in the Southern High Plains (Steward et al., 2013). As a non-renewable water source in a drought-prone region, what the future holds for the Ogallala remains to be seen (Stewart, 2003).

History of Forage Sorghum

Generally considered indigenous to Africa, sorghum has been domesticated over thousands of years (Mann et al., 1983; Vinall et al., 1936). Sorghum was introduced to the Americas by the end of the 1700s through the slave trade. The fifth most produced cereal globally, sorghum's heat- and drought-tolerant nature make it well-suited to the semi-arid southern High Plains (Brink et al., 2006). In 2007, 765,000 dryland hectares and 229,000 irrigated hectares in Texas were planted to sorghum (Texas A&M Agrilife Extension, 2008). Forage sorghums are often cultivated for single-cut silage or green chop but can grazed, grown for hay, or cut multiple times in one season (Marsalis, 2011; Machicek et al., 2019).

History of Pearl Millet

Pearl millet is believed to have originated in Sahelian Africa, and evidence points to widespread cultivation as far back as 3500 BP (Oumar et al., 2008; Brink et al., 2006). According to Brink et al. (2006), pearl millet was brought to the United States in the 19th century. Millets are a major cereal crop in India, Africa, and China, but they are grown primarily for forage in the United States. In addition to being extremely drought-resistant, pearl millet grows well on poor, low fertility soils. This makes it well-suited for regions where sorghum thrives, such as the southern High Plains (Sheahan, 2014). Pearl millet can be utilized for single- and multiple-cut hay, grazing, or green chop (Marsalis et al., 2012; Machicek et al., 2019; Crookston et al., 2020).

History of Cowpea

Indigenous to and domesticated in northeast Africa, cowpea is a major pulse crop in many countries, particularly Latin American and sub-Saharan African countries (Boukar et al., 2019; Lonardi et al., 2019; Vaillancourt and Weeden, 1992). Also known as the black-eyed pea or crowder pea, cowpea is typically grown for its grain but can be used as a vegetable or forage (Lioi et al., 2019). Well-adapted to hot, moist climates, cowpea is highly resilient and tolerant to drought, a wide variety of soils, and low fertility conditions. The crop is suitable for temperate areas of the United States (Sustainable Agriculture Network, 2012). In 2014, the United States was the 15th largest producer of cowpea, planting 12,060 hectares of the legume (FAOStat, 2017). Generally cultivated as a grain crop and culinary herb, cowpea has the potential to provide quality haulms and fodder under low input growing conditions.

Forage Production

Forage sorghum and millet are common livestock feeds globally. The crops are especially important in semi-arid to arid climates, as sorghum and pearl millet are productive in areas with annual rainfalls of less than 650 mm and 450 mm rainfall, respectively. In 2019, an estimated 58.3 billion kilograms of forage sorghum was produced globally. The United States was the largest producer of forage sorghum that year at 8.7 billion kilograms. India produced 12.5 billion of the estimated 30 billion kilograms of millet produced globally in 2016 (FAOStat, 2017). Legumes, including cowpea, provide a protein-rich food source for humans and livestock alike (Reddy et al., 2003). Approximately 8.9 billion kilograms of cowpea was produced globally in 2020. Nigeria was the largest producer of cowpea in that year with 2.6 billion kilograms (FAOStat, 2020).

Plant Morphology

Forage Sorghum

A cane-like C_4 grass, sorghum grows between 0.5 and 6 m tall and has the potential to be very stocky with stem diameters between 5 and 50 cm (QDAF, 2017). An extensive root system, a waxy cuticle on the leaves, and the ability to regulate growth in response to water stress make sorghum particularly well-adapted to areas too dry for maize production (Brink et al., 2006). Sorghum root systems can reach depths of 1.5-

2.45 m and can enter dormancy during drought conditions, making the crop a viable option for dryland producers (QDAF, 2017).

Pearl Millet

A warm-season C4 cereal, pearl millet grows between 0.5 to 3 m tall with stem diameters up to 2.5 cm (Brink et al., 2006). Leafy and prone to tillering, pearl millet is particularly well-suited to semi-arid tropical areas, as the crop responds to brief favorable conditions with rapid growth. Pearl millet roots can extend up to 2 m deep and 3 m laterally (Brück et al., 2003). Productive in both pasture and field conditions, pearl millet has an extensive range of genetic variability. This variability lends to a variety of phenotypes from which producers can select (Andrews and Kumar, 1992).

Cowpea

An annual C3 legume, cultivated cowpea phenotypes pull from a wide amount of genetic variability. Typically glabrous, cowpea can vary in growth habit between erect, prostrate, or climbing. Erect cowpea can reach 80 cm in height, lending to its success in intercropping systems. Its well-developed root system makes it well-adapted to the tropical and subtropical zones in which it is often cultivated. Domestic cowpea cultivars form symbiotic relationships with both rhizobia and mycorrhizae, potentially improving the productivity of cereals in low-input intercrop systems (OECD, 2016).

Dry Matter

Forage production of hybrid forage sorghum and sorghum-sudangrass hybrids in the Great Plains was evaluated by Venuto and Kindiger at El Reno, Oklahoma, between 2004 and 2006. Included in the experiment was a subunit harvest treatment, which consisted of one-cut (single harvest) and two-cut (late summer harvest and a ratoon harvest). Venuto and Kindiger (2008) found that mean yield was higher for the one-cut treatment than for the two-cut treatment (27.1 Mg DM ha^{-1} versus 25.5 Mg DM ha^{-1}).

Bhattarai et al. (2020b) conducted a field study at New Deal, Texas, in 2018 and 2019 examining forage yield of forage sorghum, maize, and pearl millet. Included in the study were two BMR forage sorghum cultivars, which were grown under three irrigation levels. Sorghum was harvested at the soft dough stage. Bhattarai et al. (2020b) reported that sorghum grown under deficit irrigation can yield between 29.0 and 35.4 Mg DM ha^{-1}.

Ayub et al. (2002) included forage production in their assessment of the impacts of nitrogen application and harvest date on forage sorghum in Pakistan. The results of their study showed that dry matter (DM) production increased with increased nitrogen application and increased season length. Dry matter yield 45 days after planting (DAP) ranged from 6.3 to 10.0 Mg DM ha^{-1}. When harvesting was delayed to 60 DAP, yield levels increased, ranging from 9.8 to 18.8 Mg DM ha^{-1}. The highest sorghum dry matter yield levels were produced by the 75 DAP harvest treatments, which produced between 15.8 and 38.0 Mg DM ha^{-1}. The higher yields were attributed to increased plant height and stem thickness.

Over 2009-2011, Wannasek et al. (2017) explored the dry matter production of five sorghum cultivars in field studies conducted in East Austria. Each plot was harvested five times per year beginning at 98 DAP and ending at 183 DAP. Reported dry matter yields ranged from 3.7 to 20.7 Mg ha^{-1}. The early maturing variety reached maximum yield by 113 DAP in 2011 and by 128 DAP in years 2009 and 2010, respectively. The other cultivars reached maximum dry matter by the fourth or fifth harvest in each year, with yield decreasing with subsequent harvest.

Pearl millet can yield between 10.0 to 20.0 Mg ha^{-1} in one season (Brink et al., 2006). Bhattarai et al. (2020b) reported even higher final forage yield levels between 24.8 and 33.3 Mg DM ha$^{−1}$ under deficit irrigation. In a study of pearl millet under varying irrigation and nitrogen levels, Rostamza et al. (2011) recorded total dry matter production between 10.0 and 19.5 Mg DM ha$^{−1}$. Yields in this study increased with applied water and nitrogen. Pasternak et al. (2012) reported the highest dry matter yield of pearl millet at the dough stage and the lowest at the boot stage. In that study, higher planting densities and delayed harvest produced higher millet yields, peaking at 8.5 Mg DM ha$^{−1}$.

Crookston et al. (2020) assessed water use efficiency of pearl millet in the Southern Great Plains in 2016 and 2017. The Canyon, Texas, field experiments included three treatments: irrigation level, row spacing, and tillage. Irrigation levels of high (225 total mm of water), medium (135 mm of water), and low (67.5 mm of water) were selected to mimic situations where producers are limited by diminishing saturated thickness in the aquifer. In 2016, the high irrigation treatment yielded the highest amount of dry matter at 2.2 Mg DM ha$^{−1}$. The dry matter yield between treatments was similar in 2017, with the highest amount of dry matter produced by the high irrigation treatment at 3.5 Mg DM ha$^{−1}$ (Crookston et al., 2020).

Peak dry matter in cowpea occurs at late pod fill prior to yellowing (Naab, Chimphango, and Dakora, 2009). In a three-year evaluation of rainfed forage cowpea, Gebreyowhans and Gebremeskel (2014) found that dry matter yield differed significantly between genotypes and between years. The highest dry matter yields in each year were 10.2, 8.7, and 13.7 Mg DM ha^{-1}. The lowest dry matter yields in each year were 5.4, 4.1, and 5.9 Mg DM ha^{-1}. Rao and Northup (2009) reported that dry matter production of pulse legumes in the Southern Great Plains varied depending on year and timing of precipitation. Cowpea averaged 2.4 Mg DM ha^{-1}, which was the lowest average amount in the study. Like Rao and Northup (2009), Muir et al. (2008) found the interaction of year and cultivar to significantly impact cowpea dry matter production. One cowpea cultivar yielded 4.9 and 4.1 Mg DM ha^{-1} in 2004 and 2005, respectively, while another cultivar produced 3.3 and 2.4 Mg DM ha^{-1} in those years.

Forage Sorghum Quality

Bhattaria et al. (2020b) reported that the nutritive value of sorghum differs between cultivars and years. In the 2018-2019 field study, sorghum cultivars had the lowest crude protein (CP) levels, ranging from 7.6-7.8%. Sorghum acid detergent fiber (ADF) ranged between 28.1 and 34.7%, while neutral detergent fiber (NDF) ranged between 55.4 and 61.2%. Reported sorghum in vitro total digestible dry matter (IVDMD) levels were between 61.2 and 76.7%. Sorghum had lower ADF, NDF, and IVDMD levels than maize, but it had a higher dry matter production. In 2018, sorghum produced between 28.0 and 41.0 Mg ha^{-1}, while corn produced between 18.5 to 33.2 Mg ha^{-1}. In 2019, sorghum dry matter production ranged from 16.9 to 43.0 Mg ha^{-1}, while maize dry matter production was between 15.1 to 35.9 Mg ha^{-1}. Bhattarai et al. (2020b) suggested the higher production of forage sorghum could compensate for lower nutrient concentration. Producers limited by irrigation availability could find forage sorghum a good fit when needing high dry matter production and dietary fiber.

Machicek et al. (2019) evaluated forage production and quality of forage sorghum and pearl millet during a field experiment in Canyon, Texas, from 2016 to 2017. Researchers implemented three harvesting regimes: three 30-day harvests, two 45-day harvests, and one 90-day harvest. Machicek et al. (2019) reported that forage sorghum CP levels were highest at the 30-day harvest and decreased throughout the season. The 30-day harvest treatment CP levels peaked between 10.6 and 11% before decreasing to 9.4 to 10.5% at 90 days. Single cut treatment CP levels ranged from 4.2 to 4.4%. In that treatment, ADF levels were between 38.6 and 39.9%, while NDF levels ranged from 58.3 and 62%. Additionally, TDN levels were between 57.9 and 59.5%. Machicek et al. (2019) suggested that producers looking to maximize dry matter production choose a 90-day harvest regime.

Ayub et al. (2002) identified the need to improve forage sorghum yields and quality in order to advance the livestock industry in Faisalabad, Pakistan. A field experiment in 2000 explored the relationships between nitrogen fertilizer application, harvest date, and sorghum yield and quality. The study included four nitrogen level treatments (0, 50, 100, and 150 kg N ha^{-1}) and three harvest date treatments (45, 60, and 75 DAP). Ayub et al. (2002) analyzed CP, NDF, and ADF as part of the discussion of forage quality. All treatments that included nitrogen application outperformed treatments where no nitrogen was applied. Crude protein levels peaked in the 45 DAP harvest treatments (7.0% to 10.6% CP) and decreased with each delay in harvest. The inverse relationship was observed in NDF and ADF levels. The highest levels of ADF and NDF were recorded in the 75 DAP harvest treatments, with ADF levels between 50.1% to 51.8% and NDF levels between 67.4% to 69.5%.

Worker and Marble (1968) assessed the impact of growth stage on the yield and nutritive quality of forage sorghum types in 1961 and 1962 field experiments conducted in California. Sudangrass, sorghum-sudangrass, and sorgo were included in the study with the intention to better quantify the relationship between forage yield, forage quality, and growth stage at harvest. Each type had four replicates per year and was harvested at the pasture stage, boot stage, flower stage, and soft-dough stage. Worker and Marble (1968) found that dry matter yield and percent crude fiber increased with delayed harvest. Sorgo CP peaked at 12.5% at pasture stage and decreased to 6.1% by soft dough. The percent TDN increased from 63.7 to 69.2% between the same stages. When harvested at soft dough, sorgo had a significant increase in dry matter production (30.4 Mg DM ha^{-1}). Worker and Marble (1968) suggested sorgo harvested at the soft dough stage was most suitable for silage. The results of Ayub et al. (2002) and Machicek et al. (2019) are in line with those of Worker and Marble (1968), whose research showed relationships between increased season length, increased fiber concentrations, and decreased CP.

Pearl Millet Quality

When grown under deficit irrigation, Bhattarai et al. (2020b) found higher CP concentrations in pearl millet than in forage sorghum or maize. The CP values in pearl millet ranged from 9.2% to 11.1%. Pearl millet ADF and NDF levels ranged from 28.3% to 34.9% and from 56.4% to 59.9%, respectively. These values were similar to those produced by forage sorghum in the study. The pearl millet cultivars yielded 33.3 and 30.8 Mg DM ha^{-1} in 2018 and 24.8 and 25.0 Mg DM ha^{-1} in 2019. Bhattarai et al. (2020b) concluded that pearl millet grown under deficit irrigation had dry matter production similar to maize and a nutritive profile similar to sorghum.

In a field experiment examining the performance of pearl millet under three different harvest regimes, Machicek et al. (2019) reported that pearl millet forage quality peaked at the 30-day harvest with CP levels between 11.4 and 14.6%. These levels dipped to 8.0 and 9.1% at 90-days. The single-harvest, 90-day treatment had CP levels of 4.3 and 6.29%. The ADF and NDF levels in the single-harvest treatment ranged from 38 and 39.3% and from 59.8 and 64.5%, respectively. The TDN levels were between 58.6 and 59.9% for this treatment. The nutritive values of pearl millet peaked early in the season before decreasing with increased season length. A single-cut harvest regime maximized dry matter production, while a multiple-cut harvest optimized nutritive values. Similar to Bhattarai et al. (2020b), Machicek et al. (2019) reported that pearl millet and forage sorghum had similar nutritive profiles.

In a 2007 field study, Rostamza et al. (2011) explored the interaction between irrigation and nitrogen levels and their impacts on hybrid pearl millet yield and quality.

Irrigation treatments were 40%, 60%, 80% and 100% depletion of total available soil water, while nitrogen levels were 0, 75, 150 and 225 kg N ha^{-1}. Water stress affected all included forage quality characteristics, increasing CP and crude fiber while decreasing TDN and ADF. The 100% depletion treatment produced the highest CP (19.19%) and the lowest crude fiber (36.63%). In this treatment, TDN and ADF were 51.41% and 36.44%, respectively. The lowest CP and ADF were recorded in the 40% depletion treatment at 15.6% and 32.77%, respectively. This treatment had 54.7% TDN and 39.49% crude fiber. Rostamza et al. (2011) did not find an interaction between the water and nitrogen treatments but suggested that producers with limited access to water could maximize yield and quality by matching their levels of applied water and nitrogen.

Pasternak et al. (2012) studied pearl millet under two planting densities (10,000 and 20,000 hills ha^{-1}). The study included five varieties grown under dryland conditions with three harvesting events of 50% boot, 50% anthesis, and 50% dough stage. Protein content peaked at the boot stage and decreased with plant age. At the boot and anthesis stages, the lower density treatment had the highest level of CP. At boot, the CP levels of the lower density treatment were between 14.3 and 16.8%, while CP levels in the higher density treatment ranged from 12.1 to 15.5%. At anthesis, the highest CP reported was 8.5%, and the lowest was 6.8%. At dough, CP levels were between 4.5 and 6.5%. While nutritive quality was highest at the boot stage, Pasternak et al. (2012) recommended harvesting at dough to achieve the highest dry matter yield, which concurs with the recommendations of Andrews and Kumar (1992).

Cowpea Quality

Between 2010 and 2012, Gebreyowhans and Gebremeskel (2014) examined the yield and quality of five cowpea genotypes in the semi-arid climate of Northern Ethiopia. The five genotypes were planted at the onset of the main rain season. At 50% flowering, researchers harvested the middle rows of each plot at ground level. Cowpea CP ranged from 17.7 to 18.6% with a mean of 18.1%. Mean NDF was 58.1%; mean ADF was 53%. Mean in vitro digestible organic matter was 57.3%. Based on their results, Gebreyowhans and Gebremeskel (2014) concluded that cowpea could be an advantageous addition to roughage-based diets and recommended further research into the inclusion of cowpea in the diets of ruminants.

Rao and Northup (2009) identified the need for information on quality and dry matter production of annual pulses in the Southern Great Plains. To meet this need, a study was conducted from 2003 to 2006 in Oklahoma. Field trials were conducted during the summer fallow time in a continuous no-till winter wheat system. Rao and Northup (2009) selected a common soybean [*Glycine max* (L.) Merrill] cultivar and four pulse legumes. The selected pulses were cowpea, pigeon pea [*Cajanus cajan* (L.) Millsp.], guar [*Cyamopsis tetragonoloba* (L.) Taub.], and mung bean [*Vigna radiata* (L.) Wilczek]. Inoculant was applied to the seeds of each cultivar, and cultivars were planted in the same plots each year.

Rao and Northup (2009) collected aboveground dry matter on six different dates from 45 to 120 DAP. As short season cultivars, mung bean and cowpea were the exceptions to the schedule. The digestibility of cowpea was similar to soybean (83.1 to

84.5% in vitro digestible dry matter). Researchers reported that N concentration in cowpea increased with pod development and plant maturation. Rao and Northup (2009) noted that cowpea may be a useful forage choice for producers faced with a more limited season due to its high digestibility, N concentration, and N-accumulating ability under dry conditions.

In a Texas field study from 2004 to 2005, Muir et al. (2008) addressed concerns over the effect harvesting techniques can have on warm-season legume yield and quality results. The studied legumes were soybean, cowpea, mung bean, lablab [*Lablab purpureus* (L.) Sweet], trailing wild bean [*Strophostyles helvola* (L.) Elliott.], and smooth-seeded wild bean (*Strophostyles leiosperma* Torr. & A. Gray). The harvest techniques were manually clipping plant material above the soil (7.5 or 15 cm, species dependent) or hand-plucking all leaves and pliable stems to the soil surface. There was 25 mm of irrigation applied immediately after planting; no further irrigation was applied during the season.

When plot canopy closed or 25% of an individual species reached flowering, Muir et al. (2008) undertook first and subsequent harvests. In 2004, the cowpea cultivars produced the highest and second highest CP in both early season (30.7 and 31.1%) and late season (24.8 and 26.2%). Early season ADF for the cowpea cultivars was 22.4 and 21.7%, while late season ADF was 18.9% for both cultivars. In 2005, early season CP was 24.5 and 23.8%, and late season CP was 19.2 and 20.6%. Early season ADF was 23.1 and 21.8%, and late season ADF was 19.3 and 24.5%. Cowpea CP was consistently higher than the other legumes included in the study, but the CP of all species was reported to be high enough to meet ruminant nutrition needs. The ADF across species was considered fairly low and similar to reported values for alfalfa (*Medicago sativa* L.). Muir et al. (2008), like Rao and Northup (2009), pointed to the significant impact environmental inconsistency can have on warm-season legume dry matter yield, but consistent nutritive values could help explain renewed interest in forage legumes.

Nitrate Accumulation

Nitrate accumulation poses a concern in both forage sorghum and pearl millet (QDAF, 2017; Andrews and Kumar, 1992). Dhurrin accumulation poses a lower risk in sorghum silage, but the potential for stock poisoning exists when grazing young plants and new growth. Pearl millet does not present the same cyanogenic glucoside concerns seen in sorghum (Andrews and Kumar, 1992).

Nitrate concentrations in three legumes and three cereals were examined in two field experiments conducted in 1985 and 1986. Nambiar et al. (1988) included soybean, cowpea, groundnut (*Arachis hypogaea* L.), maize, pearl millet, and sorghum in their studies in India. Conducted in raised beds, the study included three nitrogen level treatments (0, 100, 200 kg N ha^{-1}) applied in four applications (11, 31, 52, 73 DAP in 1985 and 15, 36, 55, 76 DAP in 1986). The 1985 experiment was conducted post-rainy season, while the 1986 experiment was conducted during the rainy season. Nambiar et al. (1988) reported that leaf nitrate content in all included species increased with nitrogen application. Nitrate content tended to decrease with increasing DAP and with increased rainfall. Researchers found cowpea to have the second highest nitrate concentration of the three legumes. Mean levels ranged from 309 to 4242 to 1328 µg

NO_3 g^{-1} dry leaf. Nitrate content was lower in sorghum than in maize (138 to 240 NO_3 g^{-1} dry leaf vs 696 to 1282 µg NO_3 g^{-1} dry leaf). Pearl millet nitrate content was higher than that of maize (138 to 3028 µg NO_3 g^{-1} dry leaf vs 112 to 441 µg NO_3 g^{-1} dry leaf).

Intercropping

Despite high yield potentials, cereal grass forages tend to have low CP levels, creating a limiting factor in livestock nutrition. Implementing cereal grass-legume intercrops may address this concern if soil fertility and cultivar selection allow for maintained yield levels. Root morphology contributes to the competition for nutrients between grasses and legumes. If competition for potassium and phosphorous exists, grasses will often displace legumes with their larger root systems (Frageria et al., 2006). In traditional intercrop systems, the two crops occupy the same space during the season but may not be planted or harvested at the same time (El Naim et al., 2013).

In 1995 and 1996, Ngongoni et al. (2007) examined the performance of maize-legume and sorghum-legume intercrops in Zimbabwe. The study included one maize variety, three sorghum varieties, and five legume varieties [cowpea, lablab, soybean, sunn hemp (*Crotalaria juncea* L.), and lupin (*Lupinus albus* L.)] The intercrop planting arrangement was alternating rows (1 cereal grass row: 1 legume row). At roughly 90 DAP, two rows of cereal and two rows of legume from each intercrop were harvested. Ngongoni et al. (2007) reported that cereal-lablab and cereal-cowpea intercrops had the highest intercrop yields, with cowpea contributing 2.3 Mg ha^{-1} of the sorghum-cowpea intercrop's 4.4 Mg ha^{-1} total yield. The CP content was higher in cereal-legume intercrops than in sole cereal treatments. The CP of sole sorghum was 5.4%, while the

CP of the sorghum-cowpea intercrop was 10.0%. Legume monocultures had the highest CP levels; sole cowpea had the second lowest CP at 14.6%. The sorghum-cowpea intercrop had NDF and ADF levels of 6.68 and 23.3%, respectively. Ngongoni et al. (2007) recommended legumes with trailing growth habits like lablab and cowpea to producers looking to implement 1:1 cereal-legume intercrops. These intercrops would be particularly helpful to producers looking to lower protein concentrate due to the protein rich legumes.

Darapuneni et al. (2018) evaluated the impact of canopy development and light interception on biomass yield of different sorghum-legume species. In 2008 and 2009, researchers intercropped sorghum with cowpea, pigeon pea, lima bean (*Phaseolus lunatus* L.), lablab, and pole bean (*P. vulgaris* L.) at Tucumcari and Clovis, New Mexico. Planted in a 1:1 arrangement, the treatments were irrigated throughout the season. The Tucumcari sorghum-cowpea yielded 8.9 Mg ha^{-1} 70 DAP and 14.0 Mg ha^{-1} 120 DAP. In comparison, sole sorghum yields at the same location were 9.1 and 12.6 Mg ha^{-1} on the same dates. In Clovis, sole sorghum produced 10.0 Mg ha^{-1} 78 DAP and 17.0 Mg ha^{-1} 128 DAP. The sorghum-cowpea at the location yielded 10.7 and 16.8 Mg ha^{-1} on the same dates. Darapuneni et al. (2018) noted that intercrop light interception and LAI, which are strongly associated with dry matter production, were significantly impacted by legume species.

El Naim et al. (2013) evaluated the impact of various planting arrangements on the performance of rain-fed sorghum-cowpea intercrops over 2006 and 2007. Field studies were conducted in Sudan with six treatments investigated: monoculture sorghum, monoculture cowpea, 2:2 intercrop (sorghum:cowpea), 1:1 intercrop, 2:1, and 1:2 intercrops. El Naim et al. (2013) reported that the 1:1 treatment had the highest combined yield at 7.3 Mg DM ha^{-1} with sorghum contributing 5.6 Mg DM ha^{-1}. Cowpea forage yield was highest in the monoculture treatments at 2.2 to 2.5 Mg DM ha^{-1}. Cowpea yield in the 1:1 treatment ranged from 1.7 to 1.9 Mg DM ha^{-1}, while cowpea yield in the 2:2 treatment ranged from 1.3 to 1.9 Mg DM ha^{-1}.

In response to the water scarcity common in South Africa, Chimonyo et al. (2016) examined the productivity of sorghum-cowpea and sorghum-bottle gourd [*Lagenaria siceraria* (Molina) Standl] intercrops in South Africa. Field studies in 2013 and 2014 utilized three irrigation regimes (full irrigation, deficit irrigation, and rainfed), and the sub-plots were intercrop combinations (sole sorghum, sole cowpea, sole bottle gourd, 1:1 sorghum-cowpea intercrop, and 1:1 sorghum-bottle gourd intercrop). Researchers found intercropping reduced cowpea yield by 50% in comparison to sole cropping. In 2013, monoculture cowpea yielded 0.9 Mg DM ha^{-1}, while intercropped cowpea yielded 0.6 Mg DM ha^{-1}. In 2014, monoculture and intercropped cowpea dry matter yields were 3.8 and 1.8 Mg DM ha^{-1}, respectively. Sorghum did not experience the same reduction in yield. Sole sorghum in 2013 and 2014 produced 2.9 and 2.1 Mg DM ha^{-1}, while sorghum intercropped with cowpea produced 2.9 and 2.1 Mg DM ha^{-1} in those years. Chimonyo et al. (2016) suggested sorghum-cowpea intercrops to producers in semi-arid areas, including sub-Saharan Africa.

In 1998, Mohammed et al. (2008a) evaluated the performance of rainfed single row sorghum-cowpea intercrops in Nigeria. The cowpea rows were planted one week after the sorghum rows. Sole cowpea yielded between 0.02 and 0.47 Mg DM ha^{-1} depending upon variety, while sole sorghum yielded 1.4 Mg DM ha^{-1}. Treatments with early-maturing cowpea varieties had forage sorghum dry matter yields between 4.5 and 7.8 Mg DM ha^{-1} and cowpea dry matter yields between 0.3 and 0.9 Mg DM ha^{-1}. Treatments with medium-maturing cowpea varieties had forage sorghum yields between 2.9 and 7.6 Mg DM ha^{-1} and cowpea yields between 0.3 and 1.7 Mg DM ha^{-1}. Treatments with late-maturing cowpea varieties had forage sorghum yields between 0.3 and 1.4 Mg DM ha^{-1} and cowpea yields between 0.4 and 1.2 Mg DM ha^{-1}. Mohammed et al. (2008a) found that cowpea forage yield was affected by variety while forage sorghum was not. Researchers suggested the medium-maturing varieties could improve the productivity of sorghum-cowpea intercrops.

Sogoba et al. (2020) evaluated the performance of millet-cowpea and sorghum-cowpea intercrops in southern Mali. Cereal-cowpea intercrops are common in the region, so researchers sought to quantify the benefits of cereal-cowpea intercrops to small shareholders. Sogoba et al. (2020) conducted 159 trials in 108 villages throughout 2016 and 2017. The plots were planted as 2:2 row intercrops. Row and planting distances were adjusted to account for the growth habits of the cowpea varieties.

Sogoba et al. (2020) reported that cowpea dry matter production depended on variety, with lower levels of yield variation between shorter-maturing varieties. Comparatively, long-maturing varieties showed the highest improvement in yield. Cowpea intercropped with millet produced between 0.8 and 1.6 Mg ha^{-1}, while cowpea intercropped with sorghum produced between 0.7 and 1.6 Mg ha^{-1}. Dry matter yield of millet and sorghum varied with both cowpea variety and year. Millet dry matter was improved by intercropping with cowpea, while sorghum dry matter yield was not impacted. Intercropped pearl millet produced between 3.9 and 4.1 Mg ha^{-1}, while intercropped sorghum produced between 2.8 and 3.3 Mg ha^{-1}. Sole crops of either millet or sorghum planted after a cereal-legume or cotton-cereal rotation were significantly higher-producing than sole crops planted after a cereal-cereal rotation, with millet and sorghum producing 5.4 and 2.9 Mg ha^{-1} when planted after a cereal-legume intercrop. Total gain, irrespective of cowpea variety was highest in the millet-cowpea intercropping systems.

Ntare and Williams (1992) conducted field experiments in 1988 and 1989 to determine how row arrangements and relative sowing dates of cowpea-pearl millet intercrops impacted inter-species competition and yield. The experiments were conducted near Niamey, Niger. The individual treatments were five cowpea cultivars, two planting patterns, and two sowing dates. Planting patterns were single alternating rows of each species (1:1) and double alternating rows of each species (2:2). The planting dates for the cowpea were one and three weeks after the millet was planted.

Ntare and Williams (1992) reported that both cowpea cultivar and cowpea sowing date had significant impacts on millet grain yield. Millet grain yield was reduced much more when cowpea planting was delayed by one week than when cowpea planting was delayed by three weeks. However, cowpea grain and fodder production declined up to 50% when sowed three weeks after the millet. This later sowing date shortened the cowpea growing season, resulting in faster maturation. When planted one week after millet in 1988, cowpea fodder ranged from 0.1 to 2.3 Mg ha^{-1}, but fodder production was only 0.06 to 0.5 Mg ha^{-1} when delayed by three weeks. Cowpea fodder production in 1989 ranged from 0.08 to 1.9 Mg ha^{-1} in the treatment delayed by one week and from 0.04 to 0.6 Mg ha^{-1} in the treatment delayed by three weeks. Planting arrangement was found to have no impact upon the yield of either species. The appropriate cowpea cultivar for this intercropping system would be dependent upon the goals of the producer. Regardless, the researchers found that cowpea should be sowed closer to the pearl millet sowing date to maximize yields.

In 2016 and 2017, La Guardia Nave and Corbin (2018) conducted field experiments in Tennessee to evaluate the performance of forage warm-season legumes and grasses when intercropped with maize. The treatments were monoculture maize, maize-cowpea, maize-crabgrass [*Digitaria sanguinalis* (L.) Scop.], and maize-sunn hemp. All species were planted on the same date. The maize, which was grown for silage, was planted on 76-cm row spacing, while the intercropped forages were planted on 18-cm row spacing. Measurements were taken monthly to determine the mass and nutritive value contribution of each species in the individual treatments.

La Guardia Nave and Corbin (2018) analyzed the intercrops as separate forage components and as a whole forage product. Cowpea produced an average of 2.5 Mg DM ha^{-1} in 2016 and 4.4 Mg DM ha^{-1} in 2017, which was lower than sunn hemp but close to crabgrass. There was no difference between the herbage mass of any of the treatments. The CP content in both years was highest for cowpea, ranging from 15.9 to 21.8%. Cowpea also had lower overall NDF values, with values ranging from 31.9 to

46.7%. Additionally, IVTDMD values were higher in cowpea than in the other intercrops, with values between 76.6 to 93.7%. In 2016, the maize and maize-cowpea treatments had the highest IVTDMD values, while the maize-cowpea treatment did not differ from the other intercrop systems in 2017. Maize productivity and intercrop forage mass were not reduced by the intercropping systems. The maize-cowpea intercrop was not the highest forage producer, but it did maintain forage mass production while increasing CP levels. Based on their results, La Guardia Nave and Corbin (2018) recommended the maize-cowpea intercrop above the others for producers in the Southeast United States looking to enhance forage production and grazing systems.

Islam et al. (2018) examined the forage yield and quality of different pearl millet-cowpea planting arrangements in Faisalabad, Pakistan, during the 2016 monsoon season. The treatments included alternating single rows of millet and cowpea (1:1), two rows of millet alternating with one row of cowpea (2:1), one row of millet alternating with two rows of cowpea (1:2), monoculture cowpea, and monoculture millet. Islam et al. (2018) found evidence that competition within the intercrops impacted plant population, height, and yield. Pearl millet had the highest population in the monoculture treatment (88.33 plants m^{-2}), while the 2M:1C treatment had the highest pearl millet intercrop population (58.66 plants m^{-2}). Pearl millet height was similar to the results of plant population, with the monoculture pearl millet and the 2:1 treatment producing the tallest plants with averages of 250.33 cm and 246.33 cm, respectively. Intercropping arrangements significantly impacted yield of both pearl millet and cowpea. Sole pearl millet and cowpea produced 9.9 Mg DM ha^{-1} and 6.6 Mg DM ha^{-1} of dry matter, respectively. The 2:1 treatment was the highest yielding intercrop treatment, producing 8.8 Mg DM ha^{-1} total dry matter (6.6 Mg DM ha^{-1} of pearl millet and 2.2 Mg DM ha^{-1} of cowpea). The 1:1 treatment yielded 8.3 Mg DM ha^{-1} total dry matter (4.9 Mg DM ha^{-1} of pearl millet and 3.3 Mg DM ha^{-1} of cowpea). The proportion of pearl millet to cowpea influenced the productivity of the system, which differs from the findings of Sogoba et al. (2020) and Ntare and Williams (1992).

Islam et al. (2018) examined the nutritive value of the treatments to assess whether the intercrops improved the forage value of the total product. All intercrop treatments produced higher CP levels than the monoculture treatments, and monoculture treatments produced higher crude fiber levels than all intercrops. The 1:2 treatment produced the highest CP at 14.56% and the lowest crude fiber at 22.73%. The 1:1 and 2:1 treatments produced CP levels of 12.96% and 13.5%, respectively; their crude fiber levels were 22.73% and 24.63%. The monoculture millet treatment, which had the lowest CP, produced the highest crude fiber at 30.13%. Islam et al. (2018) noted the ability of environmental conditions to influence the performance of pearl millet-cowpea intercrops but put forward the 2:1 treatment as an option to producers looking to maintain forage yield while improving CP.

Photosynthetic Active Radiation (PAR)

Photosynthetically active radiation is the portion of electromagnetic radiation utilized by plants for photosynthesis, which is light within the 400-700 nm range (Mõttus et al., 2012). As major factor in photosynthesis, PAR is a necessary input in different crop growth and yield models. Measuring PAR contributes to our understanding of a crop canopy's ability to intercept solar radiation in the 400-700 nm range. A canopy's ability to intercept light depends largely on leaf characteristics like leaf area and shape. The shading of smaller crops in intercropping systems necessitates maximizing intercepted PAR of the entire system. Kanton and Dennett (2008) suggest that smaller legumes maximize intercepted PAR more efficiently when intercropped with cereals than when planted alone.

In their examination of pearl millet, Crookston et al. (2020) reported peak PAR of 74.6% in 2016. The PAR was impacted by irrigation level in that year, with the high irrigation treatment outperforming the moderate and limited irrigation levels. In 2017, peak PAR was approximately 78%, although irrigation level did not impact PAR in that year (Crookston et al., 2020).

Machicek et al. (2019) noted that single-cut pearl millet achieved maximum PAR of 90% PAR in 2016 and 98% PAR in 2017. Alternately, single-cut forage sorghum reached 94 and 96% PAR in the same years. Forage sorghum reached maximum PAR 200 GDDs after pearl millet maximum PAR interception was reached. Pearl millet maximum PAR occurred 350 GDDs before the final harvest. These results contradict those of Crookston et al. (2020), who reported peak PAR levels of 74.6 and 78% for pearl millet in the same years.

Maughan et al. (2012) evaluated the impact of nitrogen fertilization on forage sorghum yield in 2009 and 2010. Carried out in Illinois, the study included both photoperiod-sensitive and -insensitive varieties. In both years, peak PAR was approximately 95% for all varieties. A positive correlation between nitrogen level and intercepted PAR was noted by researchers. The findings of Maughan et al. (2012) agree with those of Machicek et al. (2020), who found similar levels of intercepted PAR in sorghum.

Sousa et al. (2018) carried out two field studies to evaluate the relationship between irrigation depth and radiation use in cowpea. The 2014 and 2016 studies included four irrigation treatments corresponding to 100%, 50%, 25%, and 0% of cowpea evapotranspiration. Researchers found a positive relationship between amount of irrigation and maximum PAR. The treatment that received the most irrigation peaked at 99% interception for 8 days in 2014 and 6 days in 2016. In comparison, the treatment that received the lowest irrigation reached 97% interception for 7 days in 2014 and only 89% interception for 4 days in 2016.

In 2013 and 2014, Kamara et al. (2018) planted four cowpea varieties at three different plant densities (133,333; 266,666; and 400,000 plants ha^{-1}) in Sudan. The plots, which were not irrigated, were planted in two locations. Intercepted PAR at both locations was highest in the higher population treatments. At the first location, these treatments had intercepted PAR of 85-90%, while the second location peaked under 60%. The treatment with the lowest population measured peak PAR of 72% at the first location and 43% at the second location. These results are much lower than that of Sousa et al. (2018), but the difference can be attributed to environmental factors.

Leaf Area Index (LAI)

Leaf area index is defined as the leaf area per unit soil area ($cm^2 \bullet cm^{-2}$) (Fageria et al., 2006; Crookston et al., 2020). By measuring the amount of foliage in a canopy, LAI provides a measure of the photosynthetically active area, indicating how much light penetrates the canopy. LAI is an indicator of plant growth and contributes to dry matter production and water use efficiency. In this vein, the relationship between LAI and intercepted PAR can assist in explaining dry matter variation in crop production (Fageria et al., 2006).

Bhattarai et al. (2020a) collected LAI from pearl millet and sorghum grown under variable irrigation levels. LAI in both sorghum and pearl millet was consistently higher than maize in both years, which can likely be attributed to tillering and plant density. Highest LAI levels in all irrigation treatments were observed 75 DAP before decreasing at 90 DAP. This trend applied to all species with the exception of pearl millet in 2019, which peaked at 60 DAP. Peak sorghum LAI ranged from 4.75 to 6 in 2018 to 4 to 5 in 2019. Peak pearl millet LAI ranged from 5.3 to 5.5 in 2018 to 4.9 in 2019 (Bhattarai et al., 2020a).

As part of their discussion on the effects of irrigation on pearl millet physiology, Crookston et al. (2020) reported maximum pearl millet LAI values between 2.5 and 3.1 across two years of their study. These findings align with Rostamza et al. (2011), who found that pearl millet LAI increased with applied water and nitrogen. The highest LAI recorded was in the wettest treatment (40% deficit) at 8.7. The lowest LAI was in the driest treatment (100% deficit) at 3.1 (Rostamza et al., 2011).

In their examination of sorghum-cowpea and sorghum-bottle gourd intercrops, Chimonyo et al. (2016) recorded LAI of the sole crops and intercrops. Mean LAI for sole cowpea was 0.2. Sole cowpea LAI was highest in the full irrigation treatment (0.3) and decreased with decreased water application. In 2014, sole sorghum LAI was highest in the full irrigation treatment (0.4). Sole sorghum LAI was much higher in 2014 at 1.4 in the full irrigation treatment. The sorghum-cowpea intercrop (1:1) had a mean LAI of 0.1 with the highest sorghum-cowpea LAI recorded in the full-irrigation treatment.

Darapuneni et al. (2018) noted that intercropped legumes compensated for being shaded by adopting more prostrate growth habits. This increased light interception of the intercrop in comparison to sole sorghum. At 84 DAP, all intercrops, including sorghum-cowpea, had greater LAI than did sole sorghum. According to Darapuneni et al. (2018), a 1:1 sorghum-cowpea intercrop needed an LAI of 3.1 to achieve 90% light interception. In comparison, sole sorghum needed an LAI of 5.5 before intercepting 90% of light.

Kamara et al. (2018) found that cowpea LAI changes with plant density. The low plant density treatment (133,333 plants ha^{-1}) had peak LAI between 1.7 and 2.5. The medium plant density treatment (266,666 plants ha^{-1}) had peak LAI between 2.7 and 3.5, while the high plant density treatment (400,000 plants ha^{-1}) had LAI levels between 2.6 and 4.4. Researchers concluded that higher plant populations contributed to increased PAR interception in cowpea.

Growing Degree Days (GDD)

In a three-year field study on hybrid forage sorghum and sorghum-sudangrass forage production in the Great Plains, Venuto and Kindiger (2008) used a base temperature (T_b) of 10°C and a ceiling temperature of 30°C. In their discussion of the contribution of GDD to sorghum yield and maturity, Wannasek et al. (2017) also used a

T_b of 10°C. Alagarswamy and Ritchie (1991) grew several sorghum genotypes in growth chambers in order to create a dynamic phenology model. After scoring leaf tip appearance under a range of temperatures, researchers reported a minimum temperature of 8°C and a maximum temperature of 34°C. These parameters were applied to both sorghum and pearl millet. From 1978-1980, Ong (1983) planted pearl millet in five temperature-controlled glasshouses. The objective of the study was to identify the effect of temperature on the physiological processes of pearl millet. Ong (1983) calculated a base temperature of 12 °C for pearl millet.

Bondade and Deshpande (2021) pointed to the need to understand the effect of temperature on the rate of growth and maturation in cowpea. From March 2018 to February 2019, eleven genotypes were evaluated monthly in India. The experiment focused on determining the T_b of cowpea. They reported that cowpea T_b ranged between 9.5 and 12.1 °C. Researchers concluded that the critical minimum GDD for cowpea to flower is genotype dependent, as it ranged from 417 GDD to 595 GDD (mean of 506 GDD). This supports previous research pointing to considerable interactions between genotype and environment (Muir et al. (2008), Rao and Northup (2009), Gebreyowhans and Gebremeskel (2014)).

Hadley et al. (1983) studied the impact of photoperiod and temperature on eleven cowpea genotypes in 1978 and 1979. Grown in pots placed in growth cabinets, the plants were exposed to factorial combinations of four photoperiods (10 h, 11 h 40 min, 13 h 20 min, and 15 h) and three nighttime temperatures (14, 19, and 24 °C). Temperature did not impact rate of emergence in the experiment. Both photoperiod-sensitive and -insensitive cultivars were identified based on responses to the interaction of photoperiod and temperature. Calculated T_b in the study ranged from 4.3 to 12.2°C, leading the researchers to recommend a base temperature of 8°C for cowpea. Hadley et at. (1983) concluded that rate of development in cowpea was dependent on either photoperiod or mean temperature, partially explaining the wide variety of responses of different cultivars to field conditions.

Water Use Efficiency (WUE)

Water use efficiency (WUE) is defined as the amount of dry matter produced per unit of water transpired and can be reported in kg DM ha^{-1} mm^{-1} (Connor et al., 2011; Crookston et al., 2020). Per Connor et al. (2011), WUE of forage crops incorporates both biomass production (WUE_b) and overall performance (WUE_Y). When water is a limiting factor, maximum yield per unit of water should be prioritized over maximum yield. Crookston et al. (2020) noted the ability of pearl millet to maintain WUE under varied irrigation under limiting agronomic factors. Bhattarai et al. (2020b), Machicek et al. (2019), and Singh and Singh (1995) agree that pearl millet has a higher WUE than sorghum under severely moisture-stressed conditions.

Forage Sorghum WUE

In 1982 and 1983, Saeed and El-Nadi (1998) conducted a field experiment examining the responses of forage sorghum to three different irrigation treatments. All treatments received 70 mm of irrigated water twice prior to the introduction of the treatments. While all treatments received 700 total mm of irrigation, Saeed and El-Nadi (1998) designed treatments to fit into the categories of frequent, moderate, and infrequent irrigation schedules. Treatment A received 56 mm irrigation 10 times, Treatment B received 80 mm 7 times, and Treatment C received 104 mm five times. In both 1982 and 1983, Treatment A (frequent irrigation) had the highest dry matter yield and WUE. 1982 dry matter yield and WUE were 11,793 kg DM ha^{-1} and 85 kg DM ha^{-1} mm^{-1}; 1983 dry matter yield and WUE were 16,329 kg DM ha^{-1} and 86 kg DM ha^{-1} mm^{-1}. Saeed and El-Nadi (1998) documented a trend of increasing WUE, dry matter yield, height, and LAI with increased frequency of irrigation. They recommended that forage sorghum grown in semi-arid environments should be irrigated lightly but frequently to maximize crop performance.

Bhattarai et al. (2020a) examined the physiology of forage sorghum, pearl millet, and maize in response to deficit irrigation in Texas in 2018 and 2019. Across irrigation treatments, sorghum produced the highest dry matter in both years of the study, yielding 35,000 kg DM ha^{-1} in 2018 and 31,300 kg DM ha^{-1} in 2019. Researchers reported differences in WUE between treatments and cultivars. The WUE at final harvest in 2018 was highest for I_0, followed by treatments I_1 and I_2. This result was not repeated in 2019, with WUE for I_2 consistently outperformed I_0 and I_1 that year. Sorghum WUE outperformed both millet and maize WUE in both years (93 kg DM ha^{-1} mm^{-1} in 2018 and 116 kg DM ha^{-1} mm^{-1} in 2019). Researchers concluded that sorghum grown under limited irrigation conditions can produce more yield per unit of water than either pearl millet or maize by better utilizing stored soil moisture.

In their study on forage production and quality, Machicek et al. (2019) found sorghum WUE ranged from 9.5 to 16.4 kg DM ha^{-1} mm^{-1} depending on harvest regime and season length. Researchers reported sorghum WUE to be lower than pearl millet WUE. This contradicts the results of Bhattarai et al. (2020a), who found sorghum to have higher WUE levels under limited irrigation.

Singh and Singh (1995) evaluated the effects of three different irrigation schedules on soil-plant water relations in a field experiment in India during the 1979 and 1980 hot dry seasons. Six cultivars (two forage sorghum cultivars, two pearl millet cultivars, and two maize cultivars) were grown under three irrigation schedules (mildly stressed S_1, moderately stressed S_2, and severely stressed S_3) in 1979. The 1980 experiment evaluated three cultivars (one cultivar for each crop of interest) and added an additional irrigation schedule (unstressed S_0). Singh and Singh (1995) found that WUE in sorghum increased with increased moisture stress but peaked under moderate water stress (S_2). Researchers concluded that sorghum was the most efficient water user under moderate levels of irrigation but does not perform to that same level when under severe moisture stress.

Narayanan et al. (2013) conducted field experiments in 2009 and 2010 in Kansas. Researchers chose eight sorghum genotypes representing a wide range of vegetative transpiration efficiency values. All but one genotype were photoperiod-insensitive. Different irrigation regimes were used in 2009, but large rainfall totals that year meant that any treatment differences were removed. Narayanan et al. (2013) kept all plots well-watered in 2010.

Narayanan et al. (2013) reported that water use efficiency (WUE) among the eight genotypes studied correlated more strongly to dry matter production than to water use. In 2009, WUE ranged from 3.4 to 5.4 g kg^{-1}. WUE levels were higher in 2010 and ranged from 4.0 to 7.6 g kg^{-1}. In 2009, dry matter yields ranged from 7,970 kg ha^{-1} to 13,990 kg ha $^{-1}$, and crop water use ranged between 218 and 256 kg m^{-2}. In 2010, dry matter yields fell between 9,810 and 17,170 kg ha $^{-1}$, and crop water use was between 212 and 246 kg m^{-2}. Among the genotypes studied, those with the highest dry matter production also had the highest WUE. These results support previous research showing that increased WUE is based more on increased dry matter than on decreased water use (Bhattarai et al., 2020a). Narayanan et al. (2013) suggested further research into genotypes with high WUE to identify the mechanisms that improve dry matter production.

In their analysis of sorghum intercrops, Chimonyo et al. (2016) noted that intercropping with either cowpea or bottle gourd improved sorghum WUE by 51.6% and 72.2% in 2013 and 2014, respectively. Increased WUE of intercrops was attributed to the legumes producing higher dry matter or using less water than in their sole crops.

Pearl Millet WUE

In both years of the field study conducted by Bhattarai et al. (2020b), pearl millet produced the intermediate amount of fresh dry matter. In 2018, pearl millet dry matter production was similar to sorghum, but its yield was similar to maize in 2019. WUE of pearl millet was also intermediate in both years (92 kg DM ha^{-1} mm^{-1} in 2018 and 87 kg DM ha^{-1} mm^{-1} in 2019). Pearl millet’s consistent WUE and ability to utilize stored soil moisture make it an attractive alternative to maize.

In the field study conducted by Machicek et al. (2019), pearl millet was found to have a higher WUE than forage sorghum. The 90-day treatment pearl millet produced 25.8 kg DM ha^{-1} mm^{-1}; sorghum in the same treatment produced only 16.4 kg DM ha^{-1} mm^{-1}. While forage sorghum produced more dry matter than pearl millet, the authors suggested producers limited by available water explore a pearl millet 90-day harvest system due to its higher WUE.

In their evaluation of soil-plant water relations, Singh and Singh (1995) found that WUE of pearl millet increased with increased moisture stress. Pearl millet WUE outperformed both sorghum and maize when severely-moisture stressed. Out of the three crops evaluated, pearl millet used water most efficiently when under extremely limited irrigation. Researchers recommended sorghum remain the preferred forage crop in semi-arid regions until further research comparing sorghum and pearl millet under more extreme dry conditions was conducted.

Rostamza et al. (2011) found an interaction in water deficit levels and WUE in pearl millet. The two wettest treatments (40% and 60% deficits) had comparable WUE levels (2.8 and 3.0 kg m^{-3}). The highest WUE was recorded in the driest treatment (100% deficit) at 3.4 kg m^{-3}. Increased nitrogen application levels increased WUE as long as water availability did not inhibit fertilizer consumption.

In contrast to Singh and Singh (1995) and Rostamza et al. (2011), Crookston et al. (2020) found no difference in WUE of pearl millet grown under different irrigation levels. WUE levels in that study ranged from approximately 3.8 to 4.8 kg DM ha^{-1} mm^{-1}, pointing to the impact of other limiting agronomic factors on WUE (Crookston et al., 2020).

Cowpea WUE

Ismael and Hall (1992) conducted field studies in California in 1989 to further define the relationship between WUE and carbon-isotope discrimination in cowpea. Two pot experiments and a field study were carried out during the summer months. In the potted experiments, five cowpea genotypes were planted in pots placed on benches in a field. Well-watered until established, the plants were then split into well-watered and drought condition treatments. The treatments were replicated in an adjacent field. Ismael and Hall (1992) analyzed WU, WUE, and dry matter for the three experiments.

Ismael and Hall (1992) reported a strong correlation between total dry matter production and total water use in both pot experiments. WUE for the well-watered treatment ranged between 2.7 and 3.3 g kg^{-1}, while WUE for the drought treatment ranged from 3.4 and 4.2 g kg^{-1}. Dry matter for the pot experiments ranged between 9.6 and 60.8 g $plant^{-1}$, and water use values were between 2.8 and 18.9 kg $plant^{-1}$. The water stress of the drought treatment increased WUE of the plants by 29%. Researchers pointed to dry matter production being reduced less than water use levels.

Singh and Reddy (2011) examined the relationship between WUE and photosynthesis under well-watered and drought conditions in Mississippi in 2006. Fifteen cowpea genotypes were planted into pots filled with fine sand on 2 August. Forty pots per genotype (twenty well-watered and twenty water-stressed) were arranged randomly and well-watered until 30 DAP. Plastic sheet was applied to the soil surface of the drought treatment to prevent ET and rainfall entering the pots. Researchers simulated progressive water stress by applying 70%, 50%, 40%, and 0% irrigation over 34, 36, 40, and 50 DAP. The well-watered treatment received 100% irrigation for the entirety of the experiment.

Singh and Reddy (2011) noted inverse relationships between WUE and stomatal conductance and between WUE and soil water content. Maximum WUE of the fifteen cowpea varieties studied ranged from 81 to 186 µmol CO_2 mol^{-1} H_2O. Researchers pointed to cowpea's ability to excessively transpire under well-watered conditions without an associated increase in photosynthetic rate. This causes an indirect decrease in WUE. More drought-tolerant varieties exhibited more stomatal limitations to photosynthesis than did varieties with lower WUE. The study illustrated that cowpea maintains higher leaf water status to avoid drought impacts.

Chimonyo et al. (2016) recorded WUE in their study of sorghum-cowpea and sorghum-bottle gourd intercrops. WUE for sole cowpea dry matter production in 2013 was 3.9, 2.8, and 3.3 kg DM ha^{-1} mm^{-1} under full irrigation, deficit irrigation, and rainfed conditions. In 2014, WUE for sole cowpea improved to 5.6, 6.2, and 8.1 kg DM ha^{-1} mm^{-1} under the same treatments.

In an evaluation of cowpea performance under water stress, Anyia and Herzog (2004) cultivated ten cowpea genotypes in a growth chamber. Eighteen potted plants for each genotype were grown under well-watered conditions until flowering. At that time, the plants were allotted either to a well-watered group or a severely stressed group. WUE of the well-watered cowpea genotypes ranged from 1.6 to 3.4 g l^{-1}, while the severely stressed group had WUE levels between 1.6 to 3.1 g l^{-1}. The impact of water stress on the WUE of the ten genotypes varied widely. Some genotypes improved in WUE under water deficits up to 20%, while others saw appreciable reductions in WUE under the same conditions. Anyia and Herzog (2004) attributed this to the ability of some genotypes to maintain higher dry matter production under water stress.

Land Equivalency Ratio (LER)

Land Equivalency Ratio (LER) measures the degree to which yield per land area is impacted by intercropping systems. Monocrops are given an LER value of 1. LER assists growers in comparing intercrop yields to the yields of sole crops (El Naim et al., 2013). The formula for LER is given below.

$$LER = \frac{Crop\ A\ yield\ in\ mixture}{Crop\ A\ yield\ in\ pure\ stand} + \frac{Crop\ B\ yield\ in\ mixture}{Crop\ B\ yield\ in\ pure\ stand}$$

In their study, El Naim et al. (2013) calculated the LER for various spatial arrangements of sorghum-cowpea intercrops. In all intercrop treatments, sorghum produced LER values over 1.00, while cowpea produced values around 0.8. The 1:1 intercrop had the highest total LER at 2.1. Sorghum and cowpea LER values in the 1:1 intercrop were 1.3 and 0.8, respectively. The 2:2 treatment had a total LER value of 2.0. Sorghum LER in the 2:2 intercrop was 1.2, while the cowpea LER was 0.8. These findings are similar to those of Chimonyo et al. (2016), who noted a LER of 1.5 for 1:1 sorghum-cowpea intercrops.

In a 1998 study on 1:1 sorghum-cowpea intercrops, Mohammed et al. (2008a) found that cowpea variety impacted cowpea LER but not sorghum LER. Total LER for early-maturing cowpea variety ranged from 1.0 and 1.4, while total LER for medium- and late-maturing cowpea varieties ranged from 0.5 to 1.9 and from 0.6 and 0.9. Sorghum contribution to the LER ranged from 0.2 to 0.8. Cowpea contribution was dependent on cowpea variety. Early-maturing cowpea contributed between 0.5 to 0.8, while medium-maturing cowpea contributed between 0.2 and 1.2. Late-maturing cowpea contributed between 0.1 and 0.6. The LER results of Mohammed et al. (2008a) were lower than that of El Naim et al. (2013) and Chimonyo et al. (2016).

Gebremichael et al. (2020) conducted a two-year study on the effects of sorghum-legume intercrops on subsequent sorghum yields. When sorghum-cowpea was planted in a 1:1 arrangement, the intercrop produced a total LER of 1.3. Cowpea partial LER was 0.5, and sorghum partial LER was 0.8. The results of Gebremichael et al. (2020) support those of Mohammed et al. (2008a).

Mohammed et al. (2008b) intercropped pearl millet and cowpea in four different planting arrangements in 1999 and 2000. These arrangements were 1:1, 1:2, 2:2, and 2:4 (pearl millet : cowpea). Total LER of the 1:1 intercrop in 1999 was 1.0 with pearl millet and cowpea contributions of 0.8 and 0.2, respectively. Total LER of the 1:1 intercrop in 2000 was 1.2 with pearl millet and cowpea contributions of 0.9 and 0.3, respectively. Total LER of the 2:2 intercrop in 1999 was 1.1 with pearl millet and cowpea contributions of 0.9 and 0.2, respectively. Total LER of the 2:2 intercrop in 2000 was 1.1 with pearl millet and cowpea contributions of 0.8 and 0.3, respectively. Mohammed et al. (2008b) concluded that row arrangement did not significantly impact pearl millet partial LER, while it did impact cowpea partial LER.

Iqbal et al. (2019) assessed the performance of same row mixtures of sorghum and pearl millet with legumes. Conducted from 2014 to 2016 in Pakistan, the study included sorghum-cowpea and pearl millet-cowpea mixtures that were planted in same row arrangements at 50% of the sole species' seeding rates. Plots were flood irrigated three times through the season, and cowpea mixtures were harvested at 69 DAP. The LER of the sorghum-cowpea mixture was 1.5 with sorghum and cowpea LER contributions of 0.9 and 0.6, respectively. The pearl millet-cowpea mixture had an LER of 1.5 with millet and cowpea LER contributions of 0.9 and 0.6, respectively. The LER values of the same-row mixtures were higher than those of the 1:1 and 2:2 intercrops of Mohammed et al. (2008b). Iqbal et al. (2019) suggested cowpea's shade tolerance enabled it to perform when planted in the same row as the cereal grasses.

Sarr et al. (2008) evaluated the performance of row pearl millet-cowpea intercrops in 2001. The intercrop was planted in a 2:2 planting arrangement. The intercrop had an LER of 1.7 with millet and cowpea partial contributions of 0.6 and 1.1, respectively. These findings differ from those of Mohammed et al. (2008b) and Iqbal et al. (2019) in that cowpea LER contribution in this study was higher than that of the pearl millet.

Summary

Critical groundwater depletion levels threaten the ability of producers to meet demand for high-quality forages in the Southern High Plains. Intercropping is the practice of growing two or more crops at the same time on the same piece of land. This cropping system can increase total productivity per land unit, which contributes to maximization of system inputs like water. Identifying crop species that complement each other in growth habits, height, and season length is vital to developing a viable intercropping system. Research in the region has identified forage sorghum, pearl millet, and cowpea as well-adapted forage alternatives to maize. Common in other countries, forage sorghum-cowpea and pearl millet-cowpea intercrops seek to combine the high dry matter production of forage sorghum and pearl millet with the higher CP levels of cowpea. The objective of this study was to evaluate forage sorghum-cowpea and pearl millet-cowpea intercrops under different planting arrangements in order to identify which arrangement(s) that can yield dry matter and forage quality similar to or better than the sole grass crop.

Chapter 2

Evaluating Forage Sorghum-Cowpea and Pearl Millet-Cowpea Production and Quality in the Texas High Plains

Introduction

Declining water availability in the semi-arid southern High Plains stands in contrast with the growing demand for high-quality forages by the livestock and dairy industries. Identifying alternative forage crops and cropping systems with high water use efficiencies could be a step toward conserving the Ogallala Aquifer's remaining water. Forage sorghum [FS; *Sorghum bicolor* (L.) Moench] provides a feasible alternative forage source to maize (*Zea mays* L.), the region's largest source of forage. Drought- and heat-tolerant, sorghum produces large amounts of forage during the sweltering summer months, even under limited irrigation (Marsalis, 2011). Pearl millet [PM; *Pennisetum glaucum* (L.) Leeke] is another option that provides many of the water-saving and flexible management benefits of but without the concern of prussic acid (Bhattarai et al., 2020a). While high in digestible fiber, feed rations using forage sorghum and pearl millet must often be supplemented due to consistently low levels of crude protein (CP).

Legumes are typically higher in CP than cereal grasses. Growing cereal grasses alongside forage legumes can produce feedstuffs with higher CP levels and reduce the need to supplement rations with higher protein feeds. Forage legumes in the southern

High Plains must provide high-quality forage under water-stressed conditions. Several studies conducted in New Mexico have identified cowpea [*Vigna unguiculate* (L.) Walp] as a well-adapted, productive option (Contreras-Govea et al., 2009; Darapuneni et al., 2018). Others have long utilized cowpea in cereal grass-legume intercrops, and it could be an innovative option for producers in the Texas Panhandle.

Intercropping cereal grasses with legumes can improve forage quality and productivity when compared to row-cropping sole crops, as is typical in forage production. In row-cropping, the space between rows is left exposed during the beginning of the growing season. Water and nutrients applied to this area are lost or taken up by weeds. Solar radiation not intercepted by the target crop can be utilized by weeds and fuel evaporation of water between rows (Fordham, 1983). Intercropping cereal grasses and legumes can promote more efficient resource utilization, including light interception before canopy closure (Baligar et al., 2006). Notably, canopy closure can place the legume at a disadvantage. Unless adapted to shade, the intercrop will not be able to capture the energy needed for photosynthesis, lowering the efficiency of the intercropping system (Tsubo and Walker, 2005).

While the main goal of intercropping legumes and grasses is to harvest a more nutritious feedstuff, the land equivalency ratio (LER) of the mixture should be ≥1.00 for the intercropping system to be feasible. Previous research has shown that planting arrangement impacts mixture LER, which measures the efficacy of mixed species versus monocultures (Dariush et al., 2006; El Naim et al., 2013; Chimonyo et al., 2016).

Previous studies on cereal grass-legume intercrops in the High Plains region have identified promising mixtures that maintain yields while improving nutritive values. Forage sorghum, pearl millet, and cowpea are all well-adapted to the High Plains, and research into their performance in irrigated intercropping systems has focused on yields and nutritive values in comparison to sole crops (Contreras-Govea et al., 2009; Darapuneni et al., 2018, Machicek, 2019). The objective of this study was to evaluate the effect of three different planting arrangements on sorghum-cowpea and pearl millet-cowpea forage dry matter production and forage quality.

Methods and Materials

This study was conducted during 2020 and 2021 at the West Texas A&M University Nance Ranch near Canyon, TX (34°58’6” N, 101°47’16” W; 1097 m elevation). The experiments were carried out as an RCBD with four replicates each year. The treatments were planted on 29 June 2020 and 10 June 2021.

The experiments were planted into previously prepared, conventionally tilled Olton clay loam. Plots were 2.3 m x 6.0 m with 0.76 m borders between plots. Fully planted plots had twelve 19 -cm spaced rows that were planted with two passes a 1.52 m wide Great Plains 3p500 grain drill (Great Plains Manufacturing, Salina, KS). The grain drill made two passes to fully plant each plot. The drill was arranged to plant six rows at a time by blocking the far-right seed opener of the front and back seed boxes. Forage sorghum was planted around the field to provide a border.

Treatments were sole crop (sole forage sorghum, sole pearl millet, or sole cowpea), mixtures (forage sorghum-cowpea or pearl millet-cowpea planted in the same row), alternating rows (sorghum-cowpea 1:1 or millet-cowpea 1:1), or two rows alternating (millet-cowpea 2:2 or sorghum-cowpea 2:2). Varieties used were SP1615 sorghum (80% germination, 98% purity), “Tiflieaf 3” pearl millet (85% germination, 99.5% purity), and cowpea (80% germination, 97% purity). Cowpea seed was not inoculated prior to planting. Seeding rates were 45 kg DM ha^{-1} (1499985 seeds ha^{-1}) for forage sorghum, 28 kg DM ha^{-1} (4666676 seeds ha^{-1}) for pearl millet, and 56 kg DM ha^{-1} (571424 seeds ha^{-1}) for cowpea. Seeding rate was halved for each species in the same-row treatments only (22.5, 14, and 28 kg DM ha^{-1} for pearl millet, forage sorghum, and cowpea, respectively).

The crops were irrigated with a flow-metered drip line system with two drip lines placed 152 cm apart and emitters every 61 cm. The emitters applied 7.5 L $hour^{-1}$, similar to Crookston et al. (2020) and Machicek et al. (2019). To supplement precipitation, the experiment was irrigated one or twice per week throughout the season at rates of 25 mm per watering. Urea and superphosphate fertilizers were broadcast on the soil surface at 134 and 67 kg DM ha^{-1}, respectively, on 4 August 2020 and 21 July 2021. Weeds were hand-hoed and pulled as needed.

Plant Growth and Canopy Measurements

Plant height was measured weekly beginning 19 July 2020 and 16 July 2021. Plant height was determined by averaging the heights of two plants per species per plot. Forage canopy interception of photosynthetically active radiation (PAR) and leaf area index (LAI) was measured at 14-day intervals beginning on 22 July 2020 and 16 July 2021 using an AccuPAR Linear PAR Ceptometer, Model PAR-80 (Decagon Devices, Pullman, WA). Measurements were taken by positioning the ceptometer diagonally across three rows under full sun conditions. Percent light interception was calculated by averaging two below canopy PAR readings, dividing that average by one above canopy reading, and multiplying by 100.

Leaf Area Index

Leaf area index (LAI) was measured at 14-day intervals beginning on 22 July 2020 and 16 July 2021 using an AccuPAR Linear PAR Ceptometer, Model PAR-80 (Decagon Devices, Pullman, WA). One LAI measurement consisted of one above canopy reading and two below canopy readings. Measurements were taken by positioning the ceptometer diagonally across three rows under full sun conditions.

Soil Moisture and Nutrient Analysis

Samples were taken using a tractor-mounted Giddings hydraulic press (Giddings Machine Company Inc., Windsor, CO). Three core samples per plot were taken before planting and again after harvest. The samples were divided into two depth categories: 0-15.2 and 15.2-30.5 cm in. The soil samples were delivered to Ward Laboratory (Kearney, NE) for nutrient analysis. Samples were analyzed for nitrate-nitrogen, phosphorous, and potassium.

Forage Dry Matter and Quality Analysis

To assess the contribution of each crop species to total forage biomass, above ground biomass samples were collected at final harvest by cutting two 1 m^2 quadrats per plot at a 5 cm height. Species were bagged separately and dried for 2 days at 66°C.

Dried biomass samples were weighed to determine dry matter (DM) yield of each species and to calculate land equivalency ratio (LER). LER was calculated using:

$$LER = \frac{(Crop\ A\ yield\ in\ mixture)}{(Crop\ A\ yield\ in\ pure\ stand)} + \frac{(Crop\ B\ yield\ in\ mixture)}{(Crop\ B\ yield\ in\ pure\ stand)}.$$

Dried samples were delivered to Ward Laboratory (Kearney, NE) for nutritive analysis. Crude protein, acid detergent fiber (ADF), neutral detergent fiber (NDF), total digestible nutrients (TDN), in vitro total digestible dry matter (IVTDMD), and relative feed value (RFV) were analyzed. Samples were prepared in accordance with the NIRSC Guidelines Document (McIntosh et al., 2022). The TDN was calculated as:

$$TDN = (NFC\ x\ 0.98w) + (CP\ x\ 0.87) + (FA\ x\ 0.97\ x\ 2.25) + \frac{(NDFn\ x\ NDFDp)}{100} - 10.$$

Relative feed value (RFV) is calculated using digestible dry matter (DDM), dry matter intake (DMI), and a constant. RFV was calculated as: $\frac{(DDM\ x\ DMI)}{1.29}$.

The DDM was calculated as: $DDM = 88.9\ (-0.779\ x\ \%ADF)$.

The DMI was calculated as: $DMI = \frac{120}{\%NDF}$.

Weather Data

Weather conditions and climatic data were obtained via an on-site Campbell Scientific weather station (Table 1). Growing degree days (GDD) were calculated as:

$$\text{GDD}=\Sigma\{[\frac{\text{(daily maximum temperature+daily minimum temperature)}}{2}\text{-base temperature}\}$$

A base temperature of 10°C and a maximum temperature of 34°C were used.

Statistical Design and Analysis

The experiment had a nested design. Statistical analysis was carried out using the PROC MIXED function of SAS. An LSD ($\alpha = 0.05$) was used to test significant differences between treatment means. Significance was set at 0.05. Sole legume data was analyzed separately. Replicates were identified as unique within each year and were considered random.

Results and Discussion

Weather Conditions

The mean monthly temperatures in 2020 were similar to the 30-year average with slightly cooler temperatures in September (Table 1). However, only 28% of the 30-year average rainfall accumulated during the 2020 growing season. The growing conditions in 2021 were unfavorable due to cooler temperatures and low total rainfall. Only 64% of the 30-year average rainfall was received during the 2021 growing season, the majority of which was received during May. Rainfall accumulation in May 2021 was 239% higher than the 30-year average. For the month of July, however, only 1 mm or 1.8% of the 30-year average was received. Using the base and maximum temperature of sorghum, 1115 GDDs were accumulated during the 2020 growing season0, while 1576 GDDs were accumulated in the 2021 growing season.

Dry Matter

Maximum dry matter in 2020 was produced in the sole crop treatments with forage sorghum and pearl millet producing 16.8 and 15.4 Mg DM ha^{-1}, respectively (Figure 1). The highest producing intercrops for both forage sorghum and pearl millet in that year were the 1:1 planting arrangements, which yielded 16.2 and 13.0 Mg DM ha^{-1}, respectively. In 2021, the 1:1 forage sorghum intercrop and the mixture pearl millet intercrop produced the highest amounts of dry matter, yielding 12.4 and 8.7 Mg DM

ha^{-1}, respectively (Figure 2). Sole forage sorghum and pearl millet in that year yielded 10.3 and 8.1 Mg DM ha^{-1}, respectively. These results differ from those of Sogoba et al. (2020) who reported pearl millet-cowpea intercrops produced higher levels of dry matter than did forage sorghum-cowpea intercrops. In that study, pearl millet-cowpea intercrops produced 5.0 to 5.7 Mg DM ha^{-1}, while the forage sorghum-cowpea intercrops produced between 3.9 and 4.4 Mg DM ha^{-1}. The lower results of Sogoba et al. (2020) could be caused by the inclusion of short-season cowpea, which matures faster than the cultivar included in this study.

Legume contribution in 2020 was highest when intercropped with pearl millet. In comparison to the sole cowpea treatments, average cowpea contribution in the pearl millet intercrops was 5.0 Mg DM ha^{-1} lower than the sole cowpea yield, an 80% reduction in yield. Average cowpea yield in the forage sorghum intercrops was 5.6 Mg DM ha^{-1} lower than the sole cowpea treatment, an 88% dry matter reduction. Cowpea yield in both forage sorghum and pearl millet intercrops was similar in 2021, yielding approximately 2.70 kg DM ha^{-1} or 82% less than the sole cowpea yield.

Sogoba et al. (2020) reported similar results, measuring higher legume contribution in pearl millet-cowpea intercrops than in forage sorghum-cowpea intercrops. In that study, cowpea contribution to pearl millet-cowpea intercrops ranged from 0.8 to 1.6 Mg DM ha^{-1}, while cowpea contribution to forage sorghum-cowpea intercrops was between 0.7 to 1.6 Mg DM ha^{-1}. However, Islam et al. (2018) reported lower reductions in dry matter production of intercropped cowpea than this study. When grown as a sole crop, Islam et al. (2018) reported cowpea produced 7.2 Mg DM

ha^{-1}, while intercropped cowpea produced between 2.4 and 4.8 Mg DM ha^{-1}, which was attributed to different amounts of inter-species competition in the various planting arrangements.

In 2020, the highest performing forage sorghum intercrop was the 1:1 intercrop, which produced 0.76 Mg DM ha^{-1} less than the forage sorghum sole crop. The lowest performing intercrop that year was the 2:2 intercrop, which yielded 4.5 Mg DM ha^{-1} less than the sole sorghum crop. This pattern was repeated in 2021, with the 1:1 intercrop yielding 2.0 Mg DM ha^{-1} more than the sole sorghum crop yield. The mixture and 2:2 intercrop yields were similar and produced between 0.3 and 0.4 Mg DM ha^{-1} less than the sole sorghum crop. These results align with those of Darapuneni et al. (2013), who found that 1:1 forage sorghum-cowpea yielded more than sole sorghum by 1.4 Mg DM ha^{-1} in Tucumcari, NM. In that study, higher levels of dry matter were associated with higher LAI levels.

In 2020, average pearl millet intercrop yields were 31% lower than that of the sole pearl millet (Figure 1). The highest performing pearl millet intercrop that year was the pearl millet-cowpea 1:1, which produced 2.5 Mg DM ha^{-1} less than the pearl millet sole crop. The lowest performing pearl millet treatment in 2020 was the 2:2 intercrop, which produced 3.8 Mg DM ha^{-1} less than the pearl millet sole crop yield. In contrast, the 1:1 intercrop was the lowest performing pearl millet treatment in 2021, yielding only 0.9 Mg DM ha^{-1} less than the pearl millet sole crop. The mixture treatment yielded 0.3 Mg DM ha^{-1} more than the sole crop in that year. The 2021 results align with those of Islam et al. (2018), who reported that intercropping pearl millet and cowpea in a 1:1

arrangement resulted in lower dry matter yields in comparison to sole cropping pearl millet. Ntare and Williams (1992), however, reported that planting arrangement did not impact pearl millet-cowpea intercrop yields, which differs from the findings of this study.

Forage Quality

Crude protein levels did not differ between planting arrangements within grass species in either year (Tables 2 and 3). Maximum crude protein (CP) among all intercrop treatments in 2020 was produced in the mixed pearl millet-cowpea intercrop at 11.5% CP (Table 2). The forage sorghum treatment with the highest CP in 2020 was the 1:1 intercrop with 8.9% CP, which was slightly lower than the 9.9% CP of the sole pearl millet. In 2021, the 2:2 pearl millet-cowpea intercrop had the highest CP at 8.3%. The 2:2 forage sorghum intercrop had the highest CP of the forage sorghum treatments at 7.2%. These results are slightly lower than those of Ngongoni et al. (2007), who reported CP levels of 10.0% in 2:2 forage sorghum-cowpea intercrops.

Crude protein in the forage sorghum treatments did not differ in either year, averaging 8.3% in 2020 and 6.4% in 2021. This is contrary to Ngongoni et al. (2007), who reported that forage sorghum-cowpea intercrops had higher CP levels than that of sole sorghum. When planted as a monoculture, forage sorghum crude protein (CP) averaged 6.6% across both years (Tables 2 and 3). This is slightly higher CP in comparison to Machicek et al. (2019), who reported that forage sorghum had CP levels between 4.2 and 4.4% at 90 DAP.

No difference was found in ADF, NDF, IVTDMD, or TDN values between forage sorghum planting arrangements in 2020 or 2021. In 2020, the average ADF value of the forage sorghum treatments was 45.2%, and the sorghum treatments had an average NDF of 74.1%. In 2021, average ADF of the forage sorghum treatments was 42.6%, and the forage sorghum treatments had an average NDF of 69.7%. The average TDN value for all sorghum treatments in 2021 was 53.9%, and the average IVTDMD was 67.6%. Ngongoni et al. (2007) reported much lower NDF and ADF values for sorghum-cowpea intercrops, with a 1:1 arrangement in their study measuring 23.3% ADF and 6.7% NDF. Crude protein in the pearl millet-cowpea intercrops did not differ in either year. When planted as a monoculture, pearl millet CP averaged 6.4 to 9.9% across both years. In 2020, CP levels ranged from 10.8 to 11.5%. This range decreased to 7.2 to 8.3% in 2021. This study reported lower CP levels when compared to Islam et al. (2018), who found CP levels between 13.0 and 14.6% in pearl millet-cowpea intercrops.

No difference was found in ADF, NDF, IVTDMD, or TDN values between pearl millet planting arrangements in 2020 or 2021. In 2020, pearl millet treatments produced an average ADF value of 41.7% and average NDF value of 69.2%. In 2021, pearl millet treatments had an average ADF of 40.1% and an average NDF of 65.9%. Average pearl millet IVTDMD 2020 was 69.7%, while average IVTDMD in 2021 was 72.8% in 2021. Similarly, the average pearl millet treatment TDN in 2020 was 54.9% and increased slightly in 2021, ranging from 56.8%. The RFV For the pearl millet intercrops was observed to range between 4.8 to 5% between the two study years. The IVTDMD for the treatments ranged between 1.9 and 3.7% between the two study years.

Crop Canopy Development

Leaf Area Index

In 2020, the LAI all pearl millet treatments peaked at 950 GDDs before decreasing to the end of the season (Figure 3). In contrast, all forage sorghum treatments excluding the 1:1 intercrop peaked at 1064 GDDs. Pearl millet treatments had higher peak LAI values in 2020 than did the forage sorghum treatments (7.7 vs 7.5). In 2021, the LAI in all treatments peaked at 1286 GDDs, which was the end of the growing season (Figure 4). In that year, average peak LAI in the pearl millet treatments was 7.1, while the forage sorghum treatments had an average peak LAI of 6.9. Overall, average peak LAI was 8% higher in 2020 than in 2021. These values are higher than those found by Machicek et al. (2019), who reported peak LAI values between 4.5 and 4.7 in forage sorghum and between 3.9 and 5.6 in pearl millet in the same location.

In 2020, the forage sorghum-cowpea 2:2 intercrop had the highest LAI of the forage sorghum treatments at 8.4 at 1064 GDDs. That value is 7% higher than the peak LAI of the sole sorghum treatment (7.8). The lowest LAI of the forage sorghum treatments was measured in the forage sorghum-cowpea 1:1 treatment, which peaked at 7.0 at 950 GDDs before dropping to 6.4 at the end of the season. In 2021, both the 1:1 and 2:2 forage sorghum-cowpea intercrops had higher peak LAI values than did the sole forage sorghum treatment. The forage sorghum-cowpea 2:2 treatment had the highest LAI at 7.4, which was 13% higher than the sole crop’s peak LAI of 6.5. The mixture intercrop had the lowest LAI at 6.4.

The peak LAI values of sole sorghum in this study are higher than those of Machicek et al. (2019) and Bhattarai et al. (2020a). Bhattarai et al. (2020a) reported peak LAI values between 4 to 6 for sole forage sorghum. Chimonyo et al. (2016) published much lower LAI values of 0.4 to 0.6 for 1:1 sorghum-cowpea intercrops. In addition to hail events during that study, the researchers used wider row spacings and lower plant populations, which could contribute to the lower LAI values of Chimonyo et al. (2016) when compared to this study.

In 2020, the highest LAI in the pearl millet treatments was measured in the sole crop, which peaked at 8.6 at 950 GDDs. This is 16% higher than the peak LAI of the mixture and 2:2 intercrops, which reached peak LAI values of 7.4 and 7.5, respectively. The 1:1 pearl millet intercrop had the lowest LAI value at 7.3. All pearl millet treatments during the 2020 season peaked at 950 GDDs before declining at the end of the growing season. The 2:2 pearl millet intercrop had the highest LAI value of the pearl millet treatments in 2021. It reached a peak LAI of 7.6 at 1286 GDDs, which was the end of the growing season. This value is 19% higher than the peak LAI of the sole pearl millet treatment. The sole pearl millet treatment had the lowest LAI of the 2021 pearl millet treatments at 6.4. All pearl millet treatments in 2021 peaked at the end of season (1286 GDDs).

The values for sole pearl millet in this study are similar to those of Bhattarai et al. (2020a), who reported maximum LAI values between 4.9 to 5.5. Comparatively, the results of Crookston et al. (2020) showed lower peak LAI values for sole pearl millet between 2.5 to 3.1. Agronomic factors like the inclusion of wider row spacing (76 cm), a no-till treatment, and varied irrigation in Crookston et al. (2020) and may have contributed to the lower recorded LAI values.

In both years and both crops, the 2:2 planting arrangement produced the highest intercrop LAI values. In 2020, the lowest intercrop LAI was measured in the 1:1 intercrops of both grass species. However, the lowest intercrop LAI in 2021 was measured in the mixture treatments of both grass crops.

The sole cowpea treatment had the lowest LAI in both years. In 2020, sole cowpea peaked at 6.7 at 717 GDDs before declining to 4.3 at the end of the growing season. This trend was not repeated in 2021, where the sole cowpea treatment peaked at 1286 GDDs, which was the end of the growing season. At that time, the treatment peaked at 6.2, which was only 0.2 and 0.4 lower than sole pearl millet and forage sorghum, respectively.

Photosynthetic Active Radiation

Across both years and grass species, end of season intercepted PAR varied only 2.6% between all intercrops (Figures 5 and 6). Among the 2020 forage sorghum treatments, the 1:1 and 2:2 intercrops both reached peak intercepted PAR levels of 99% at 1064 GDDs, which was the end of the season (Figure 5). The sole forage sorghum and mixture intercrop reached peak intercepted PAR levels of 99 and 98%, respectively, at 950 GDDs. In 2021, all forage sorghum treatments reached peak intercepted PAR of 98% at the end of the season, which was 1286 GDDs (Figure 6). Machicek et al. (2019) reported similar maximum PAR values between 94 and 96% between 1250 and 1450

GDDs. Maughan et al. (2012) reported a similar maximum PAR value of 95% at the end of the growing season.

Across all pearl millet treatments in 2020, sole pearl millet was the only treatment to peak at the end of the season, reaching 99% intercepted PAR. The 2:2 intercrop reached maximum PAR the earliest, measuring 98% at 717 GDDs. In 2021, all pearl millet treatments peaked at 1286 GDDs. All 2021 pearl millet treatments excluding the 1:1 intercrop reached maximum intercepted PAR between 96 to 98%. This is similar to Machicek et al. (2019), who measured maximum PAR of 90 to 98% in sole pearl millet. However, Crookston et al. (2020) reported much lower maximum PAR of sole pearl millet, with peak levels of 74.6 to 78%, likely due to the inclusion of treatments involving no-till, wider row spacing, and variable irrigation in that study.

In 2020, the mixture planting arrangement for both grass species achieved peak intercepted PAR at 1064 GDDs, which was the end of the season. The forage sorghum mixture achieved PAR of 98%, while the pearl millet mixture achieved maximum PAR of 99%. In 2021, the mixture planting arrangements of both grass species reached peak intercepted PAR of 98% at 1286 GDDs, which was the end of the season.

In 2020, the 1:1 pearl millet treatment reached a maximum PAR of 99% at 828 GDDs, 236 GDDs before the 1:1 forage sorghum treatment peaked at 98% PAR. Alternatively, in 2021, the 1:1 treatments of both grass species peaked at 1286 GDDs just before harvest. The 1:1 forage sorghum reached a maximum PAR of 98%, while the 1:1 pearl millet had a maximum PAR of 97%.

In 2020, the 2:2 pearl millet treatment reached peak intercepted PAR mid-season, measuring 98% at 717 GDDs. In contrast, the 2:2 forage sorghum treatment that year reached a maximum PAR of 99% at 1064 GDDs. In 2021, the 2:2 treatment of both grass species reached maximum intercepted PAR of 98% at the end of the season.

Irrigated Water Use Efficiency

In 2020 and 2021, irrigated water use efficiency (WUE) was measured (Table 4). Irrigated WUE did not differ between treatments within crop in either year. Average forage sorghum irrigated WUE was 49.4 kg DM ha^{-1} mm^{-1} in 2020 and 39.5 in 2021. These values were lower than the traditional WUE for sole sorghum reported by Saeed and El-Nadi (1998), who reported WUE between 85 and 86 kg DM ha^{-1} mm^{-1}, and Bhattarai et al. (2020a), who reported WUE between 93 and 116 kg DM ha^{-1} mm^{-1}. However, the results of this study were higher than those of Machicek et al. (2019), who measured WUE between 9.5 and 16.4 kg DM ha^{-1} mm^{-1} for sole sorghum. While lower than the WUE results of other forage sorghum-cowpea intercrops, the results of this study showed an improvement in WUE in comparison to sole forage sorghum previously planted in the same area (Machicek et al., 2019).

The pearl millet treatments had an average irrigated WUE of 38.1 kg DM ha^{-1} mm^{-1} in both years. This value is lower than the traditional WUE reported by Singh and Singh (1995) and Bhattarai et al. (2020a) for sole pearl millet, who reported WUE between 87 and 92 kg DM ha^{-1} mm^{-1}. However, the results of this study were higher than those for the pearl millet sole crops of Machicek et al. (2019), who reported WUE of 25.8 kg DM ha^{-1} mm^{-1}, and Crookston et al. (2020), who reported WUE between 3.8

and 4.8 kg DM ha^{-1} mm^{-1}. While the results of this study were lower than those of other studies on pearl millet-cowpea intercropping, they were higher than sole pearl millet planted in the same area previously.

Irrigated WUE of sole cowpea was higher than the intercropped cowpea in both years. In 2020, irrigated WUE of sole cowpea was 18.6 kg DM ha^{-1} mm^{-1}, while it was only 10.9 kg DM ha^{-1} mm^{-1} in 2021. Average irrigated WUE of cowpea intercropped with forage sorghum was 2.2 kg DM ha^{-1} mm^{-1} in 2020, while it was an average of 2.0 kg DM ha^{-1} mm^{-1} in 2021. Average irrigated WUE of cowpea intercropped with pearl millet was 3.8 kg DM ha^{-1} mm^{-1} in 2020, while it was an average of 2.0 kg DM ha^{-1} mm^{-1} in 2021 Chimonyo et al. (2016) reported higher WUE of sorghum-cowpea intercrops and sole cowpea than found in this study with WUE between 2.75 and 8.12 kg DM ha^{-1} mm^{-1}.

The results of this study align with those of Singh and Singh (1995), who concluded that forage sorghum had higher WUE than pearl millet under moderate water stress. However, Chimonyo et al. (2016) reported that intercropping sorghum and cowpea improved WUE over that of sole forage sorghum. The results of this study differ from those findings, as there was no difference between WUE of the treatments. This could partially be attributed to the inclusion of deficit and dryland treatments in Chimonyo et al. (2016) and Singh and Singh (1995), which concluded that sole sorghum and sorghum intercrops are more water efficient under moderate water stress. Water was not a limiting factor in this study, so the lack of water stress could be a factor in the lower WUE levels.

Land Equivalency Ratio (LER)

The LER for the forage sorghum treatments averaged 0.91 in 2020 and 1.24 in 2021 (Tables 5 and 6). Legume contribution to the total forage dry matter was low, ranging from 5.4% in 2020 to 5.8% in 2021. The LER results of forage sorghum-cowpea in this study were lower than that of the 1.54 reported by Chimonyo et al. (2016) and the 2.01 to 2.11 reported by El Naim et al. (2013). The results of this study were comparable to the LER results of Mohammed et al. (2008a), who reported LER values between 0.52 to 1.38 depending on cowpea variety.

The LER for the pearl millet intercrops averaged 0.91 in 2020 and 1.1 in 2021. Legume contribution averaged 10.7% in 2020 and 7.7% in 2021The LER results of this study are similar to that of Mohammed et al. (2008b), although the legume contributions reported by those authors were higher. Iqbal et al. (2019) and Sarr et al. (2008) both reported higher LER and legume contribution values than found in this study. Iqbal et al. (2019) reported an LER for a mixture pearl millet-cowpea intercrop of 1.5 with a legume contribution of 0.6. Sarr et al. (2008) reported an LER of 1.7 for 2:2 pearl millet-cowpea intercrop, with a legume contribution of 1.1. These differences could be attributed to cultivar selection and environmental factors, both of which widely impact the performance of cowpea.

Conclusion

Grass-legume intercrops present a strategy to intensify production under increasingly limited groundwater availability. There was no difference found in yield or nutritive value between planting arrangements within grass species in either year of this study.

The maintenance of yields across planting arrangements suggests both forage sorghum-cowpea and pearl millet-cowpea intercrops could remain viable options for forage producers in the Southern Great Plains. In 2021, the LER of all but one intercrop treatment (1:1 pearl millet) was higher than that of the sole grass crops. However, the lower LER values of 2020 lean toward the findings of Islam et al. (2018) that environmental conditions have profound influence on the performance of grass-legume intercrops. Further research could explore the influence of environmental factors on the performance of forage sorghum-cowpea and pearl millet-cowpea intercrops and the economics of adopting intercrops in the Southern Great Plains.

TABLES

Table 1. Average monthly air temperature and total rainfall near Canyon, TX for 2020-2021. Thirty-year averages (30-yr) were calculated from data collected from the National Weather Service Forecast Office from 1989-2019.

	Average air temperature			Total rainfall		
Month	2020	2021‡	30-yr	2020	2021‡	30-yr
		C°			mm	
May	20.0†	17.2	19.7	21	146	61
June	24.9	24.8	24.6	20	10	70
July	26.4	24.4	26.5	23	1	57
August	26.4	24.9	25.6	19	35	77
September	19.1	22.8	21.5	7	10	51

† Weather data collected from the National Weather Service Forecast Office (Amarillo, TX) for Canyon, TX, for May and June 2020 only.

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

Table 2. Forage sorghum (FS)-cowpea (C) and pearl millet (PM)-C dry matter (DM) and forage quality means for CP, ADF, NDF, TDN, and RFV in 2020, near Canyon, TX.

	2020						
	DM	CP†	ADF	NDF	IVTDMD	TDN	RFV
Treatment	Mg ha^{-1}	--%--					
FS PA							
FS	16.8a‡	7.4a	46.0a	75.5a	63.9a	50.1a	65.3a
FS-C	13.7a	8.8a	44.1a	72.8a	65.7a	52.2a	69.8a
FS-C 1:1	16.2a	8.9a	45.2a	74.0a	64.8a	50.9a	67.8a
FS-C 2:2	12.3a	8.1a	45.4a	73.9a	64.8a	50.9a	67.3a
SE	0.77	0.37	0.50	0.62	0.51	0.57	1.04
PM PA							
PM	15.4a	9.9a	42.2a	71.2a	69.2a	54.4a	73.3a
PM-C	11.9a	11.5a	40.8a	67.6a	70.8a	56.0a	78.3a
PM-C 1:1	13.0a	10.9a	41.6a	69.2a	69.7a	55.1a	76.0a
PM-C 2:2	11.7a	10.8a	42.3a	68.8a	69.2a	54.3a	76.0a
SE	0.65	0.27	0.33	0.53	0.35	0.38	0.86
C*	6.3	12.1	40.3	48.3	75.3	56.6a	117.5

†CP = crude protein, ADF = acid detergent fiber, NDF = neutral detergent fiber, IVTDMD = in vitro total dry matter digestibility, TDN = total digestible nutrients, RFV = relative feed value

‡Columns with same lowercase letter are not different within crop, within year with α<0.05.

*Cowpea presented for visual comparison only.

Table 3. Forage sorghum (FS)-cowpea (C) and pearl millet (PM)-C dry matter (DM) and forage quality means for CP, ADF, NDF, TDN, and RFV in 2021, near Canyon, TX.

	2021						
	DM	CP†	ADF	NDF	IVTDMD	TDN	RFV
Treatment	Mg ha^{-1}	----------------	----------------	--------%--------	----------------	----------------	
FS PA							
FS	10.3a‡	5.7a	42.7a	71.9a	66.6a	53.9a	72.0a
FS-C	10.0a	6.6a	42.8a	69.3a	67.4a	53.7a	74.8a
FS-C 1:1	12.4a	6.1a	42.7a	69.7a	67.5a	53.9a	74.5a
FS-C 2:2	10.0a	7.2a	42.3a	68.0a	68.8a	54.3a	76.5a
SE	0.83	0.29	0.37	0.70	0.42	0.42	1.04
PM PA							
PM	8.1a	6.4a	40.0a	68.4a	72.7a	57.0a	78.8a
PM-C	8.7a	8.1a	39.6a	65.0a	72.7a	57.4a	83.3a
PM-C 1:1	7.2a	7.2a	40.4a	64.7a	73.0a	56.5a	83.3a
PM-C 2:2	8.4a	8.3a	40.6a	65.9a	72.9a	56.2a	80.8a
SE	0.44	0.44	0.45	0.91	0.51	0.46	1.64
C*	3.3	15.7	38.2	48.6	76.3	59.1	114.0

†CP = crude protein, ADF = acid detergent fiber, NDF = neutral detergent fiber, IVTDMD = in vitro total dry matter digestibility, TDN = total digestible nutrients, RFV = relative feed value

‡Columns with same lowercase letter are not different within crop, within year with α<0.05.

*Cowpea presented for visual comparison only.

Table 4. Dry matter (DM), applied irrigation, and irrigated water use efficiency (WUE) means of forage sorghum (FS)-cowpea (C) and pearl millet (PM)-cowpea intercrops by planting arrangement (PA) near Canyon, TX, in 2020 and 2021.

	2020		
	DM	Total Irrigation	Irrigated WUE
Treatment	kg ha^{-1}	mm	kg ha^{-1} mm^{-1}
FS PA			Total
FS	16.9814a†	340	49.4a
FS-C	13746a	340	40.4a
FS-C 1:1	16158a	340	47.5a
FS-C 2:2	12270a	340	36.1a
PM PA			
PM	15419a	340	45.3a
PM-C	11893a	340	34.9a
PM-C 1:1	12959a	340	38.1a
PM-C 2:2	11647a	340	34.2a
C*	6315	340	18.5
	2021		
FS PA			Total
FS	10324†	305	33.8a
FS-C	9983a	305	40.4a
FS-C 1:1	12365a	305	47.5a
FS-C 2:2	9960a	305	36.1a
PM PA			
PM	8091a	305	45.3a
PM-C	8682a	305	34.9a
PM-C 1:1	7196a	305	38.1a
PM-C 2:2	8371a	305	34.2a
C	3334	305	18.5

†Columns with same lowercase letter are not different within crop, within year with $\alpha<0.05$.
Irrigated WUE = DM / (Total irrigation)

Table 5. Yield components of forage sorghum-cowpea and pearl millet cowpea intercrops in 2020 at Canyon, Texas, by planting arrangement.

	Sorghum DM	Cowpea DM†	Mixture DM		
Planting Arrangement	-------------------------Mg ha^{-1}		--------------------------	% Legume	LER†
Sole	16.8a‡	-	-	-	1.00a
Mixture	13.0a	0.7a	13.7a	5.1a	0.93a
1:1	15.5a	0.6a	16.2a	4.1a	1.06a
2:2	11.4a	0.9a	12.3a	7.1a	0.87a

	Pearl Millet DM	Cowpea DM	Mixture DM		
Planting Arrangement	-------------------------Mg ha^{-1}		--------------------------	% Legume	LER
Sole	15.4a	-	-	-	1.00a
Mixture	10.7a	1.2a	11.9a	10.3a	0.89a
1:1	12.1a	0.9a	13.0a	6.9a	0.92a
2:2	9.9a	1.7a	11.6a	14.8a	0.92a

†The LER of all sole crops is 1. Cowpea sole crop yields averaged 6.3 Mg ha-'.

‡Columns with same lowercase letter are not different within crop, within year with $\alpha<0.05$.

LER = (Crop A yield in mixture) / (Crop A yield in pure stand) + (Crop B yield in mixture) / (Crop B yield in pure stand)

Table 6. Yield components of forage sorghum-cowpea and pearl millet cowpea intercrops in 2021 at Canyon, Texas, by planting arrangement.

	Sorghum DM	Cowpea DM	Mixture DM		
Planting Arrangement	--------------------------Mg ha^{-1}		--------------------------	% Legume	LER
Sole	10.3a‡	-	-	-	1.00a
Mixture	9.4a	0.6a	9984a	5.9a	1.09a
1:1	12.0a	0.4a	12365a	2.9a	1.27a
2:2	9.1a	0.8a	9961a	8.5a	1.36a

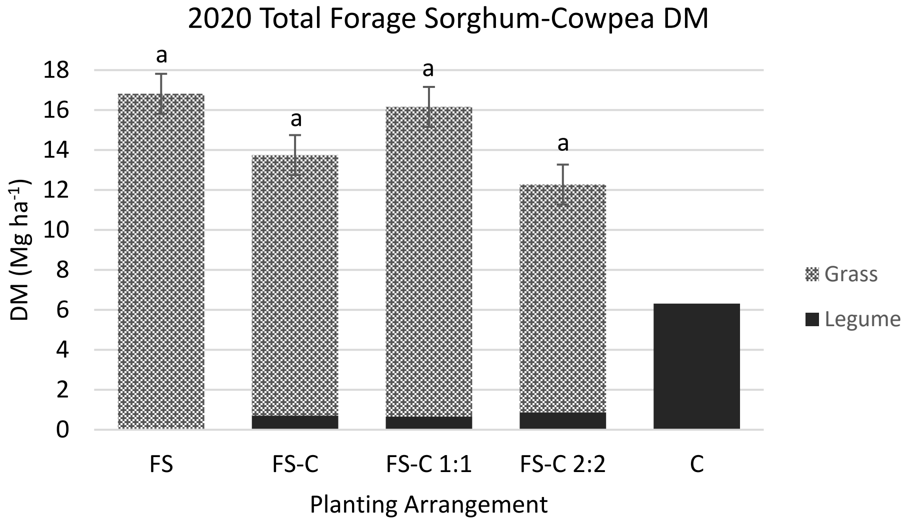
	Pearl Millet DM	Cowpea DM	Mixture DM		
Planting Arrangement	--------------------------Mg ha^{-1}		--------------------------	% Legume	LER
Sole	8.1a	-	-	-	1.00a
Mixture	8.3a	0.3a	8.7a	3.6a	1.13a
1:1	6.6a	0.6a	7.2a	8.2a	0.99a
2:2	7.4a	0.9a	8.4a	11.1a	1.19a

† The LER of all sole crops is 1. Cowpea sole crop DM yields averaged 3.3 Mg ha-1.

‡ Columns with same lowercase letter are not different within crop, within year with α<0.05.

LER = (Crop A yield in mixture) / (Crop A yield in pure stand) + (Crop B yield in mixture) / (Crop B yield in pure stand)

FIGURES



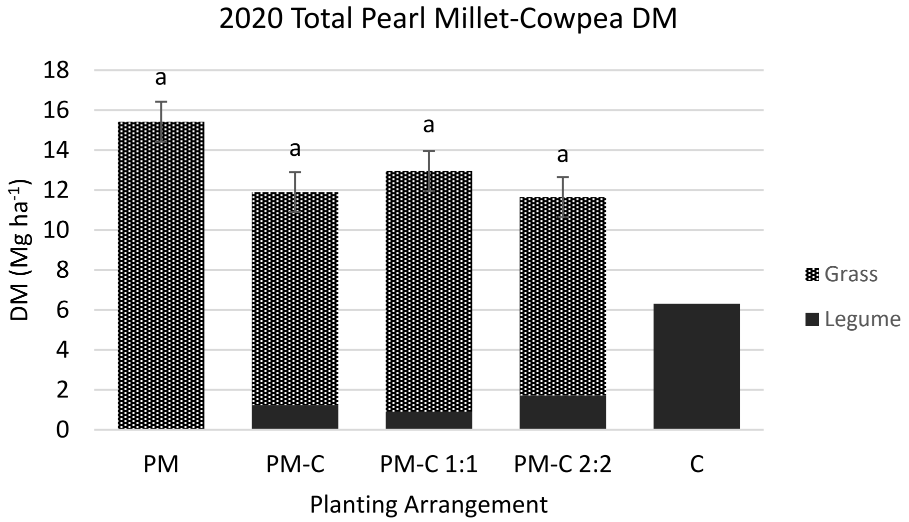


Figure 1. Total forage sorghum (FS)-cowpea (C) and pearl millet (PM)-C intercrop dry matter (DM) in 2020 near Canyon, TX. Data with the same letter within species and year are not different between planting arrangements ($p<0.05$). Cowpea data presented for visual comparison only.

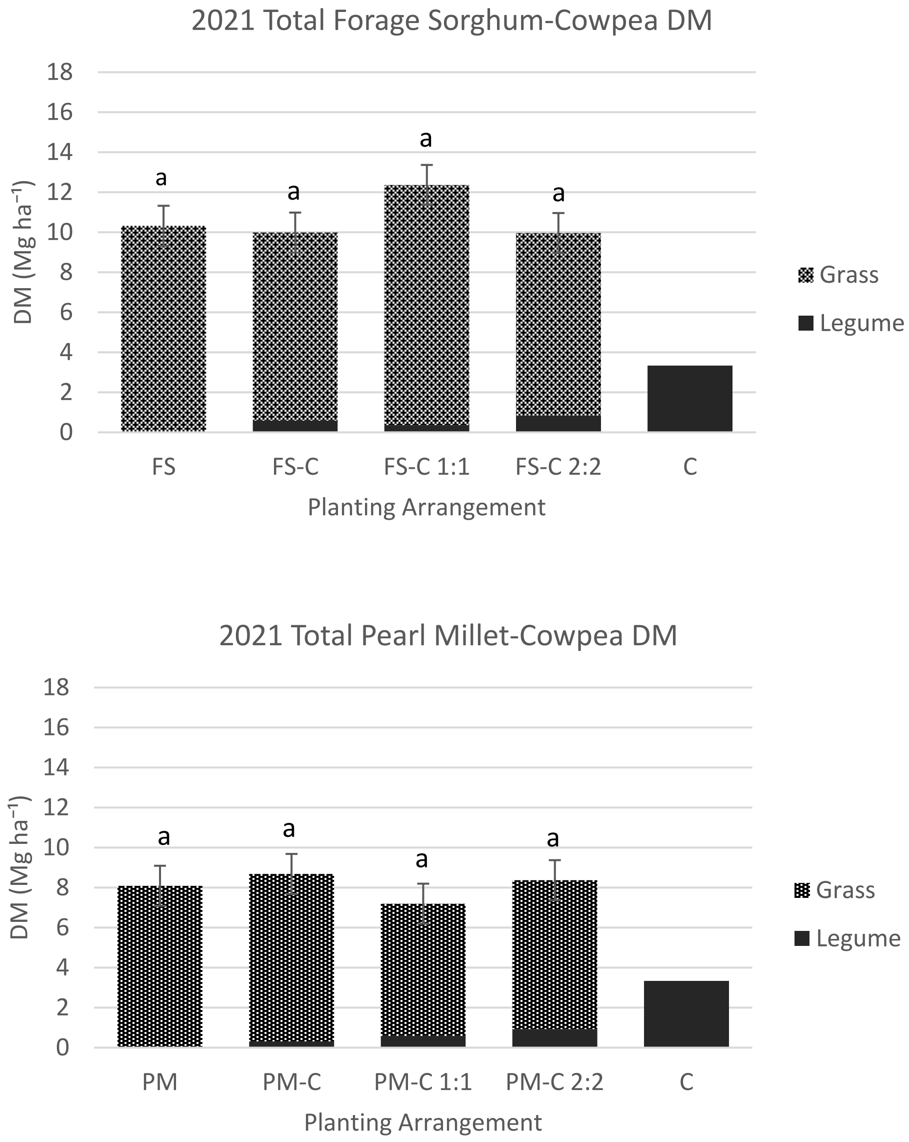


Figure 2. Total forage sorghum (FS)-cowpea (C) and pearl millet (PM)-C intercrop dry matter (DM) in 2021 near Canyon, TX. Data with the same letter within species and year are not different between planting arrangements ($p<0.05$). Cowpea data presented for visual comparison only.

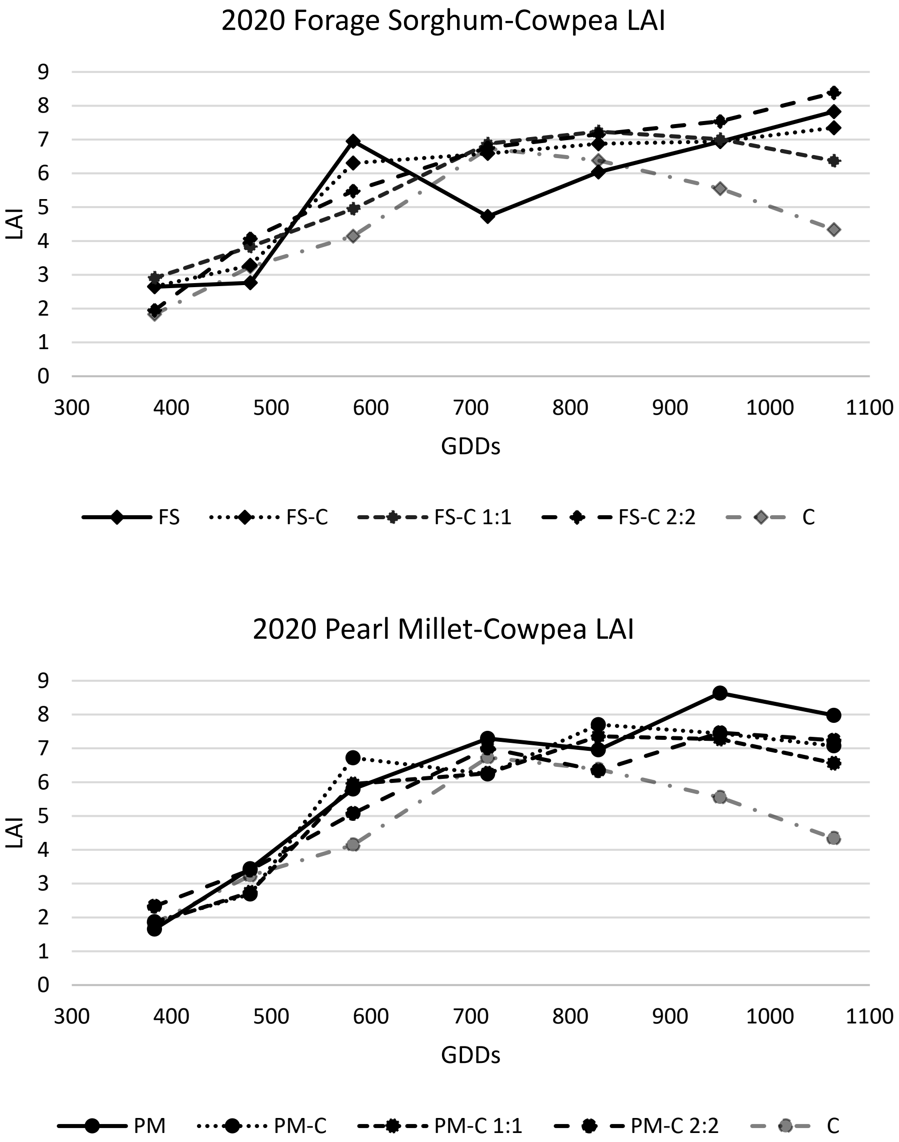


Figure 3. Forage sorghum (FS)-cowpea (C) and pearl millet (PM)-C leaf area index (LAI) by planting arrangement in 2020, near Canyon, TX. Cowpea LAI presented for visual comparison only.

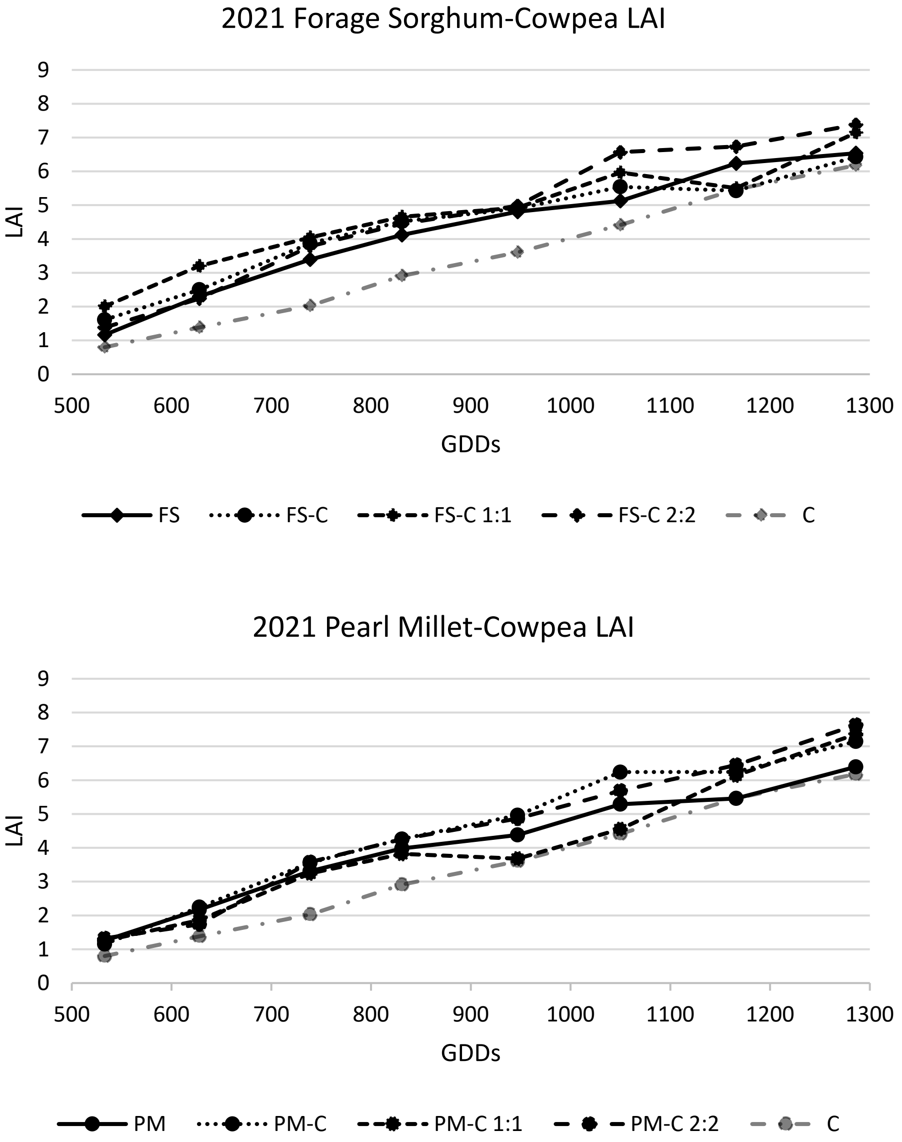
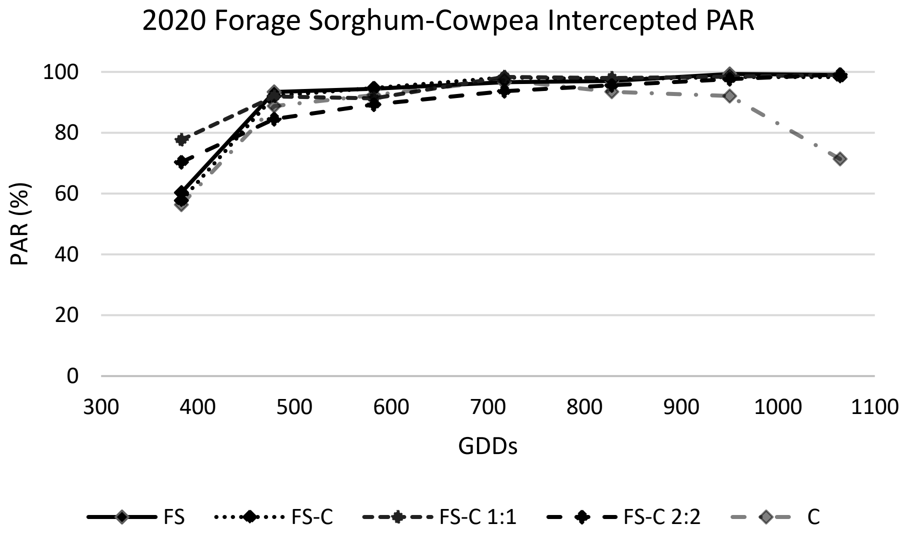


Figure 4. Forage sorghum (FS)-cowpea (C) and pearl millet (PM)-C leaf area index (LAI) by planting arrangement in 2021, near Canyon, TX. Cowpea LAI presented for visual comparison only.



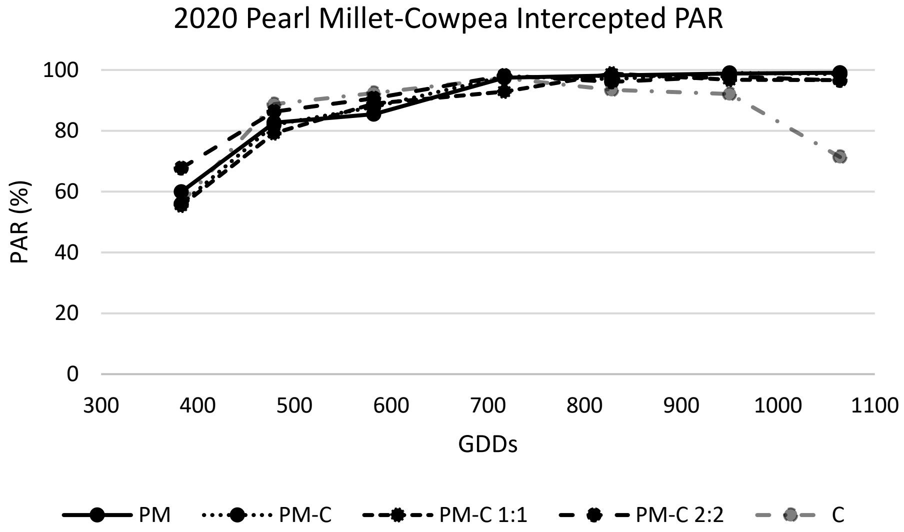
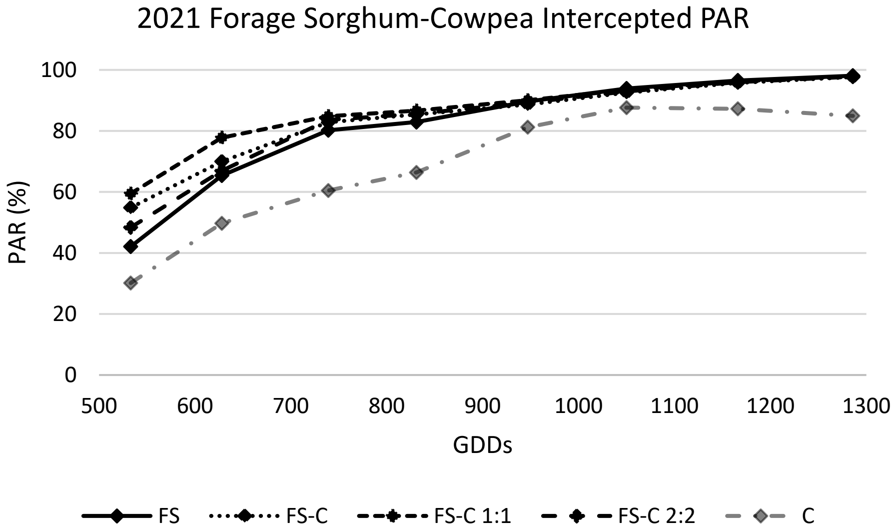


Figure 5. Forage sorghum (FS)-cowpea (C) and pearl millet (PM)-C intercepted photosynthetically active radiation (PAR) by planting arrangement in 2021, near Canyon, TX. Cowpea PAR presented for visual comparison only.



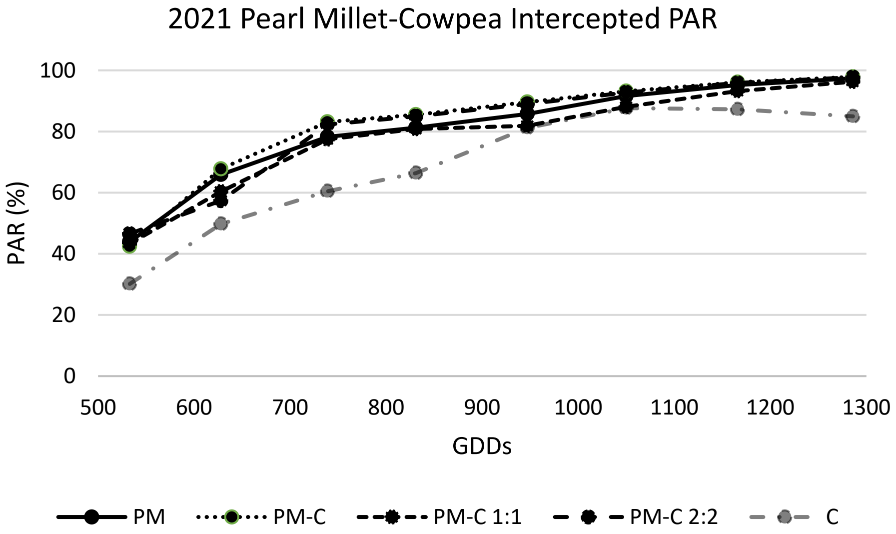


Figure 6. Forage sorghum (FS)-cowpea (C) and pearl millet (PM)-C intercepted photosynthetically active radiation (PAR) by planting arrangement in 2021, near Canyon, TX. Cowpea PAR presented for visual comparison only.

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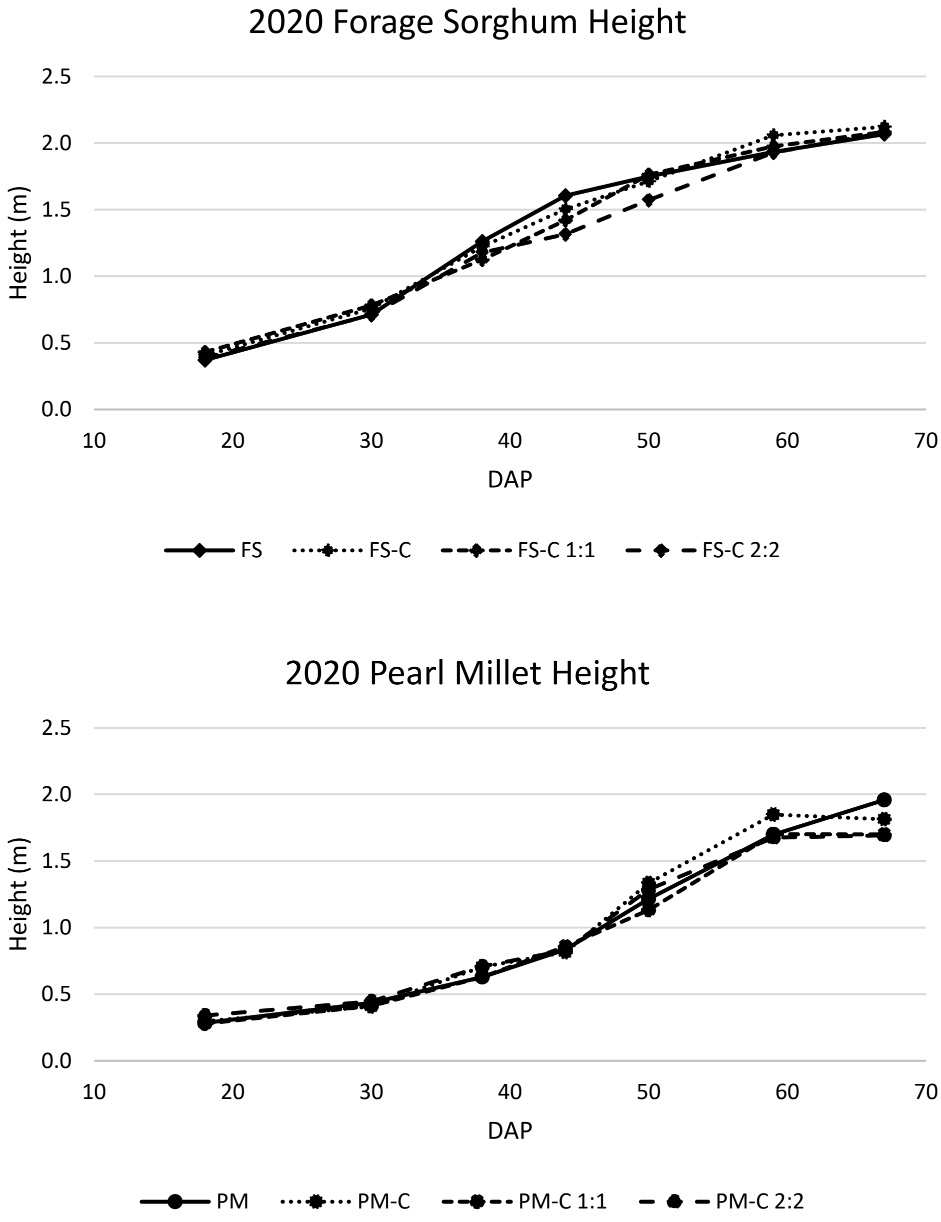
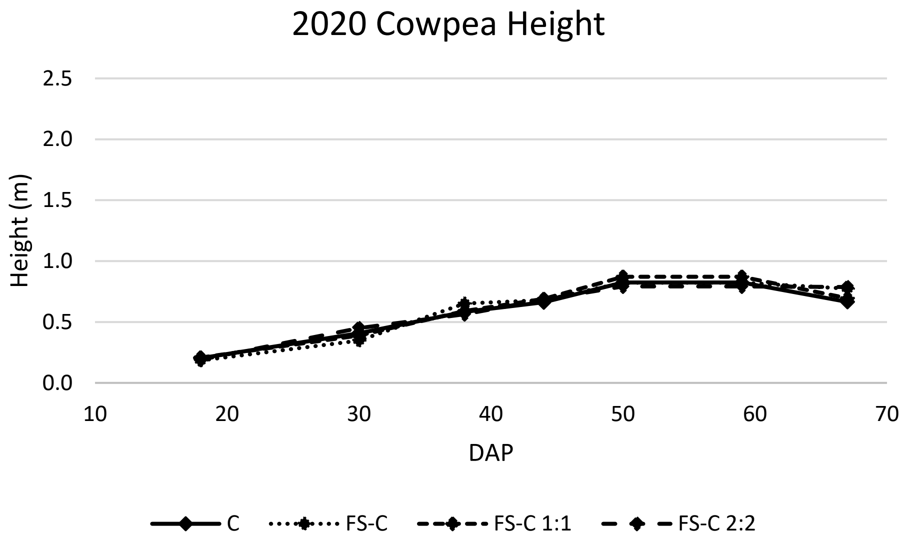
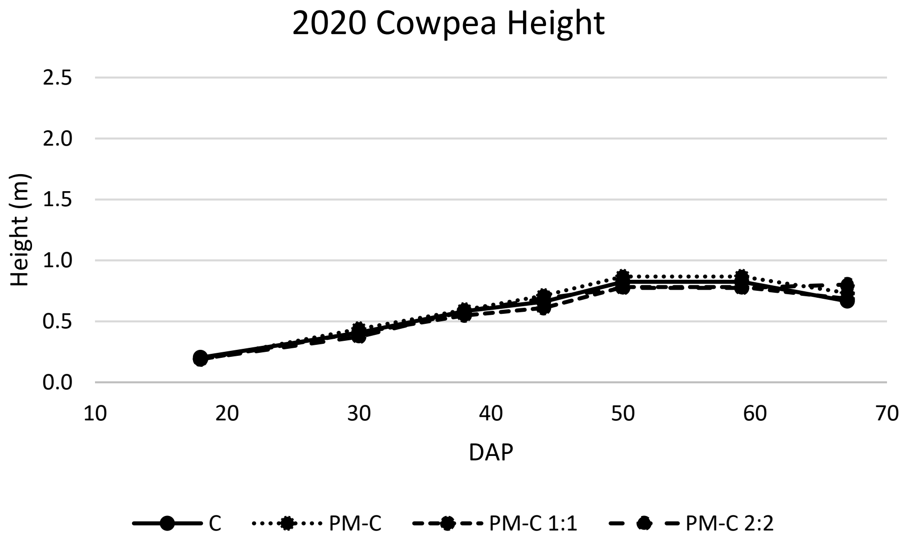
APPENDIX


2020 Forage Sorghum Height

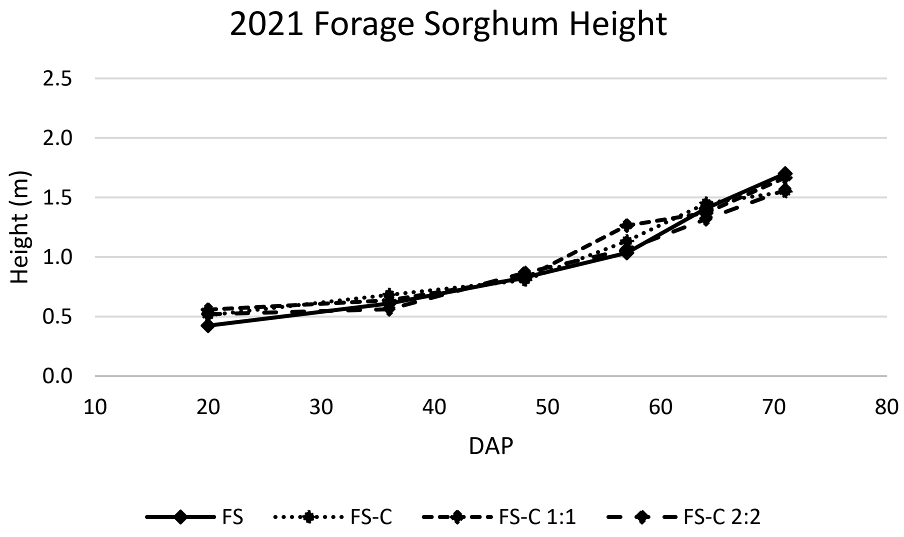
2020 Pearl Millet Height

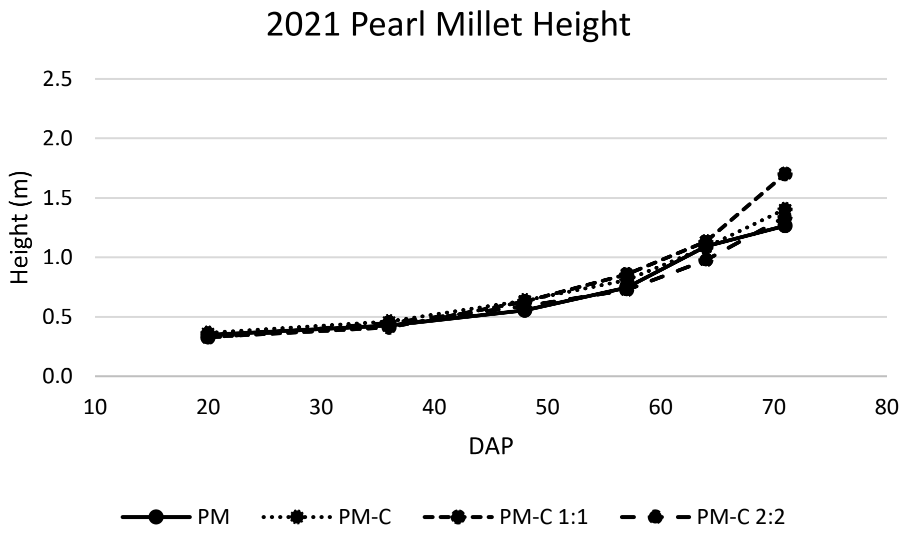
Supplementary Figure 1. Plant height means of forage sorghum (FS) and pearl millet (PM) in forage sorghum-cowpea (C) and pearl millet-cowpea intercrops by planting arrangement in 2020, near Canyon, TX.



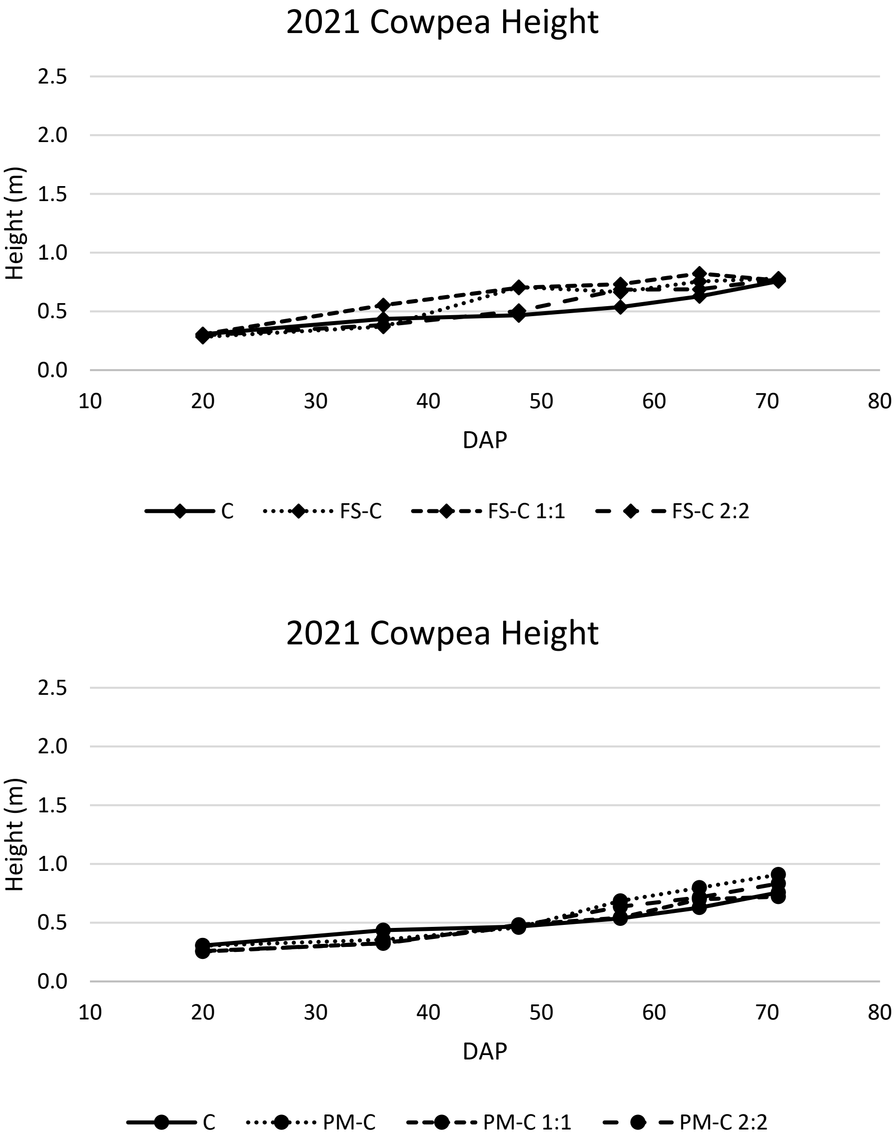


Supplementary Figure 2. Plant height means of cowpea in forage sorghum (FS)-cowpea (C) and pearl millet (PM)-cowpea intercrops by planting arrangement in 2020, near Canyon, TX.





Supplementary Figure 3. Plant height means of forage sorghum (FS) and pearl millet (PM) in forage sorghum-cowpea (C) and pearl millet-cowpea intercrops by planting arrangement in 2021, near Canyon, TX.



Supplementary Figure 4. Plant height means of cowpea in forage sorghum (FS)-cowpea (C) and pearl millet (PM)-cowpea intercrops by planting arrangement in 2021, near Canyon, TX