EVALUATING CAPABILITIES OF NOVEL WARM-SEASON CROPS TO FILL FORAGE DEFICIT PERIODS IN THE SOUTHERN GREAT PLAINS

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Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 2019

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Date of Degree: DECEMBER, 2019

Title of Study: EVALUATING CAPABILITIES OF NOVEL WARM-SEASON CROPS TO FILL FORAGE DEFICIT PERIODS IN THE SOUTHERN GREAT PLAINS

Major Field: CROP SCIENCE

Abstract: Low nutritive value of perennial grasses during mid-late summer limits stocker cattle production in the Southern Great Plains (SGP). Our objectives were to explore annual crop species that might fit as a summer forage, and quantify their forage potentials under the highly variable agro-climatic conditions of the SGP. A field experiment compared the seasonal changes in abovegroung dry matter (ADM), leaf-to-stem ratio, and chemical composition of tepary bean (*Phaseolus acutifolius*) and guar (*Cyamopsis tetragonoloba*) to soybean (*Glycine max*). Tepary bean outperformed soybean and guar by producing greater ADM (6.5 Mg ha^{-1}) with a leaf-to-stem ratio of 3.1 at 65 days after planting (DAP), and its chemical composition also remained superior and consistent throughout the growing season. Secondly, ten mothbean (*Vigna aconitifolia*) lines were evaluated for their forage, grain or green manure potentials. Mothbean lines generated a ADM range of 7.3-18.1 Mg ha^{-1} with 10.8-14.6% crude protein (CP), 32.0-41.7% neutral detergent fiber (NDF), 20.7-29.6% acid detergent fiber (ADF), and 73-84% in vitro true digestibility (IVTD) at 100 DAP. Third, eleven finger millet (*Eleusine coracana*) accessions were assessed for their adaptability and forage characterization under the SGP conditions. Finger millet accessions resulted in ADM ranging from 5.0-12.3 Mg ha^{-1}, which contained 10.5-15.6% CP, 59.8-73.4% NDF, 26.8-38.2% ADF, and 59.7-73.0% IVTD at 165 DAP. Finally, a greenhouse study was conducted to compare vegetative growth and physiological responses of mothbean, tepary and guar under four different water regimes. Tepary bean showed the lowest stomatal conductance (g_s) and photosynthetic rate (A), but it maintained the highest instantaneous water use efficiency (WUE_i) among species under water-stressed treatments. At final harvest (77 DAP), the ADM generated by tepary bean was 38-60% and 41-56% higher than guar and mothbean, respectively, across four water deficits. Tepary bean was identified as the most drought-tolerant and reliable option for SGP among the tested species, considering its higher biomass production, WUE_i, leaf-to-stem ratio, and consistent nutritive value when grown as a summer forage. Future research should focus on defining management practices for growing these novel crops in extensive production settings for grazing or hay.

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CHAPTER I

POTENTIAL SUMMER ANNUAL FORAGES FOR THE SOUTHERN GREAT PLAINS: INTRODUCTION AND LITERATURE REVIEW

A major part of this review chapter was published as "Baath, G.S., B.K. Northup, A.C. Rocateli, P.H. Gowda, and J.P.S. Neel. 2015. Forage potential of summer annual grain legumes in the Southern Great Plains. Agron J. 110:2198-2210."

1.1. INTRODUCTION

The United States ranks first among the beef producing countries and accounted for approximately 18.2% of global production of beef in 2013 (FAOSTAT, 2017). Although there has been a decline in per capita beef consumption within the United States (from 33.8 kg in 1985 to 25.3 kg in 2016), total consumption (about 11.6 billion kg) has continually increased due to population growth (Kannan et al., 2017). Cattle production accounted for approximately $60 billion in total agricultural sales and was the largest among US agricultural commodities, followed by $49 billion from corn sales in 2015 (USDA NASS, 2016). The United States exported about $6.3 billion in beef products to Japan, South Korea, Mexico, Canada, Hong Kong and other countries in 2015 (USDA ERS, 2017a).

Agriculture in the SGP is equally important to global, national, and regional food security, particularly the beef production system that developed during the late 20th Century. Annually, millions of weaned calves from cow-calf operations throughout the United States are sold through local markets (Peel, 2003). Most of these animals are eventually feedlot finished in the SGP and processed at co-located slaughter and packer facilities (Figure 1.1.). However, there is insufficient feedlot space to accommodate all these animals simultaneously, so large numbers spend time grazing pasture in the SGP as stocker cattle, generating low-cost gain until space becomes available (Peel, 2003). Texas, Kansas, and Oklahoma represent the majority of the SGP region and are among the top five beef producing states (Figure 1.1.), which further outlines the importance of the region to beef production.

The SGP is comprised of diverse land types including native range, introduced perennial grasses, dryland cropping, and irrigated areas. It spreads from the front range of the Rocky Mountains in Colorado and New Mexico, eastward through Oklahoma and southern Kansas (Figure 1.1.). The periphery swings across northwest Texas to the southern limit of New Mexico through the Texas Panhandle and adjoining areas of west Texas and eastern New Mexico. Elevation in the region ranges from 1,500-1,800 m at the western edge, to < 600 m on the eastern and southern edges (Savage and Costello, 1948). The amount and timing of precipitation received annually in the SGP varies throughout the region, ranging from 395-449 mm in the western areas to 755-890 mm along the eastern fringe (Figure 1.1.; Figure 1.2.). About half of the total annual rainfall occurs during late-spring through summer (May-September). However, the region frequently encounters prolonged periods of drought, where amount and occurrence of rainfall during this period is erratic on a monthly basis (Schneider and Garbrecht, 2003; Rao and Northup, 2011a; Patrignani et al., 2014). Maximum air temperatures are relatively uniform with low levels of variability (29.5-33˚C), particularly during June through August (Figure 1.3.). Minimum air temperatures are more variable (14-21˚C) during summer. The level of variability in precipitation and temperature within the SGP presents a challenge for defining new crops with the potential to function on a region-wide basis.

The dominant elements of forage systems that support weight gain by yearling stocker cattle in the SGP utilize annual winter wheat and perennial (native prairie or introduced) warm-season grasses (Phillips and Coleman, 1995; Redmon et al., 1995; Peel, 2003). These systems (Figure 1.4.) have been effective for grazing yearling stocker cattle but with shortcomings related to limited availability of high quality forage in May, and from August through October (Phillips and Coleman, 1995; Coleman and Forbes, 1998; Northup et al., 2007). Combinations of forages arrayed in larger systems are required to lengthen the time that high quality forage is available and limit shortcomings during the production cycle (Northup et al., 2007; Phillips et al., 2009; Patrignani et al., 2014).

Winter wheat is also the primary agricultural crop planted in the SGP region, with over 2.6 million hectares planted annually in Oklahoma (Hossain et al., 2004). It serves producers as a drought avoidance crop, by taking advantage of soil moisture that accumulates during summer fallow (June through August) and September rainfall, and matures early enough to avoid the hot and dry conditions that occur during summer. Summer fallow serves as a technique to minimize risk of crop failure. Aiken et al. (2013) reported 18 and 31% reductions in wheat forage and grain yields, respectively due to 132 mm less soil water in wheat-soybean rotations compared to wheat-fallow rotations in western Kansas. However, there are numerous sustainability issues for wheat-fallow rotations, including poor precipitation use efficiency (Farahani et al., 1998), potentially greater soil erosion, and decreased soil organic carbon and nitrogen, depending on tillage system (Kelley and Sweeney, 2010). No-till systems can help alleviate such problems, but there has been limited adoption by wheat producers in the region. For example, a survey in Oklahoma (Hossain et al., 2004) reported roughly 89% of producers who use continuous winter wheat-summer fallow systems apply conventional tillage to 56% of the total area planted to wheat, while 36% and 8% of cropland is managed by reduced and no-till systems, respectively (Conservation Technology Information Center, 2004).

Wheat is a dynamic and flexible crop capable of producing multiple commodities within one growing season, based on its competing values as grain, hay and livestock gain (Peel, 2003; Decker et al., 2009; Edwards et al., 2011). Wheat serves as the primary source of high quality forage for stocker cattle from late fall through early spring (Figure 1.4.). According to a survey in Oklahoma (Hossain et al., 2004), the intended use of winter wheat was 20% for pasture only, 49% for a dual-purpose role (winter grazing and spring grain), and 31% for production of grain only. Wheat grown for grain is planted during late September through early October to avoid the potential occurrence of dry growing conditions in early September (Lyon et al., 2007). Alternatively, dual-purpose wheat (graze-grain) is generally planted in early to mid-September and grazed from mid-November until the occurrence of first hollow stem (early March) stage of growth (Fieser et al., 2006; Edwards et al., 2011). Wheat grown for grazed pasture (graze-out) is planted in early September, to maximize forage production during November through April (Figure 1.4.).

Pasture of perennial warm-season grasses including bermudagrass [*Cynodon dactylon* (L.) Pers.], Old World bluestems *(Bothriochloa* spp.), and native prairie have been the traditional forages for summer grazing, though mostly in support of cow-calf operations (Figure 1.4.; Phillips and Coleman, 1995; Coleman and Forbes, 1998; Rao et al., 2002). In contrast to cow-calf pairs, production of stocker cattle requires large amount of high quality forage in order to fulfill both growth and maintenance requirements of animals (Phillips and Coleman, 1995; Neel et al., 2007). An important issue for grazing stocker cattle is the decline in forage quality of these perennial grasses with maturation as the growing season advances (Coleman and Forbes, 1998). This decline becomes a limiting factor for stocker production without protein supplementation (Philips and Coleman, 1995; NRC, 1996). Given the growth patterns of winter wheat and the more typical perennial warm-season grasses, there is no single forage crop capable of providing nutritious biomass for year-round grazing. A possible solution is to find nutritious forages, which can fill the void during mid-summer and enhance sustainability of forage-stocker systems. However, any such potential crops must also perform well within the widely adopted systems used in production of the primary crop of the SGP (winter wheat) without generating deficits in soil resources that are important to establishment and growth by winter wheat (Rao and Northup, 2009b).

Work undertaken over the last two decades in the SGP has searched for annual grain legumes (pulses) with potential to serve as either forages or green manures (Rao et al., 2005; 2007; Rao and Northup, 2009a; 2011b; Butler and Muir, 2012; Northup and

Rao, 2015). Some of the tested pulses showed potential to provide high-N biomass (Rao and Northup, 2009a; 2012; 2013; Northup and Rao, 2015). However, the presence of large-diameter, low quality stems limits the value of many pulses for grazing (Rao and Northup, 2013). Further, the biomass of many species contains secondary plant compounds, especially tannins and other polyphenolics (Price et al., 1980; Kumar and Singh, 1984; Ajayi et al., 2009). Both factors restricted grazing to short time periods of the lifecycle of the tested pulses (Rao and Northup, 2012). Such issues and limitations for the tested legumes indicate there is still a need for research to identify alternate species of pulses that may serve as sources of high N biomass for agroecosystems in the SGP.

Worldwide, roughly 7,000 plant species are cultivated to feed humans. However, just 20 species meet 90% of the total food requirements for humans (Chivenge et al., 2015). The remaining species are underutilized or their use is restricted to limited areas such as Sub-Saharan Africa. Such a large pool means there is a diverse range of underutilized crops that may have the capacity to provide grazing or hay for cattle in the SGP. Identifying well-adapted legume species from such a broad base of crops for use as forage in stocker production systems of the SGP could enhance the sustainability of stocker-based grazing systems, or increase agro-ecosystem diversity by providing new cover or grain crops.

Selection of the proper crop for summer periods will be critical due to the agro-climatic conditions in the SGP. Most crops tend to function better in systems with greater amounts of available water due to reduced competition for this limited resource (Snapp et al., 2005). However, competition for moisture between summer crops and subsequent winter wheat in the SGP needs addressing, as irrigation is not an option for most producers in the region. The performance of dryland winter wheat, particularly during the period of germination and early fall growth, relies on moisture stored in the soil profile (Rao and Northup, 2011b). Therefore, the emphasis should be on identifying crops that are productive in response to the variable climate of the SGP, and have limited effects on soil moisture to minimize carry-over effects on subsequent wheat crops. This review discusses soybean, the most commonly used legume in the SGP and some species from arid and semi-arid regions that might fit the forage-livestock production systems of the SGP as summer forage.

1.2. SOYBEAN

Soybean, an oil-seed legume species, originated and was domesticated in south China (Guo et al., 2010). It is widely grown across many parts of the world. Soybean has an erect growth habit and can grow to a height of 1.3 m (Lee et al., 1996). Cultivated soybeans have trifoliate leaves with oval to lanceolate leaflets and purple, pink or bluish papilionaceous flowers. It has a well-developed tap root system, which can extend to a depth of 1.5 m (Ordonez et al., 2018). The United States is currently the largest producer (35% of world production) of soybeans, followed by Brazil (29%), and Argentina (17.5%) (FAOSTAT, 2017; Ciampitti and Salvagiotti, 2018). Within the United States, 31 states produce soybean with Illinois, Iowa, Minnesota, and Indiana as the top four producers (USDA NASS, 2017)

Soybean is largely grown for grain, which has multiple uses. Raw soybean contains 360 g kg^{-1} protein, 300 g kg^{-1} carbohydrates, 200 g kg^{-1} fat, and many essential vitamins and minerals (USDA ARS, 2016) and serves as an important component in the diets of vegetarians and vegans across the world. The consumption of soybean foods has continuously increased in last few decades due to its health benefits, including prevention of cancer, obesity, and diabetes, lowering of cholesterol, and protection against kidney and bowel disease (Friedman and Brandon, 2001). Further, soybean oil is currently a leading feedstock for biodiesel production in the United States and considered as an effective and economical component in products such as paints, resins, rubber, polyurethane, and coatings.

Within soybean, variation in the day length which initiates the physiological transition from vegetative to reproductive stages results in cultivars being classified into different maturity groups (Zhang et al., 2017). It generally takes 100-120 d to reach maturity with mid-late maturity group cultivars in the SGP (Rao and Northup, 2009a; Wagle et al., 2017). The late maturity group cultivars produce greater forage biomass during September-October than other cultivars in the SGP (Rao et al., 2005). Soybean requires a temperature range of 25-30˚C for an optimum growth and its reproduction is affected at temperatures above 35˚C (Salem et al., 2007; Setiyono et al., 2007). The total water requirement of soybean ranges from 420-540 mm in the Midwest region of United States (Payero et al., 2005; Suyker and Verma, 2008).

Soybean was primarily grown as a forage crop after its introduction into the United States in the mid-19th century (Probst and Judd, 1983). However, grain acreage surpassed forage acreage by 1941 due to the demand for its oil and meal. In the last two decades, there has been renewed interest by researchers in evaluating soybean as forage crop in the United States (Sheaffer et al., 2001; Rao and Northup, 2008; Nielson, 2011; Beck et al., 2017). In the SGP, forage yields of soybean ranged between 1.1-5.4 Mg ha^{-1} with 150-190 g kg^{-1} CP and 740-790 g kg^{-1} in vitro digestible dry matter (IVDDM; Rao et al., 2005; MacKown et al., 2009; Rao and Northup, 2009a; Northup and Rao, 2015). It was found to produce insufficient biomass (<1.5 Mg ha^{-1}) in the years receiving low precipitation (<50 mm) during early summer (Rao and Northup, 2009; Foster et al., 2009; Northup and Rao, 2015), which would cause limitations on forage intake by yearling cattle (Coleman et al., 2010). Double-cropping winter wheat and soybean is an important practice in many regions across the United States (Knott et al., 2018). However, when the approach was investigated by MacKown et al. (2007) and Northup and Rao (2015) in the SGP, it was found to be ineffective. Given the variability associated with spring and summer rainfall patterns in the SGP, productivity of double-cropped soybean as forage was reported as marginal (1.17 Mg ha^{-1}), and the function of soybean as a green manure failed to offer any N benefit to winter wheat or increase C and N concentrations after 3-4 y (MacKown et al., 2007; Northup and Rao, 2015).

1.3. TEPARY BEAN

Tepary bean [*Phaseolus acutifolius* (A.) Gray] is an annual legume native to northwestern Mexico and the southwestern United States. Cultivated tepary beans have either bush or semi-vine type growth forms, with pointed trifoliate leaves, short and slightly hairy green pods, and deep tap root systems (Stephens, 1994). Tepary bean was once a vital part of the 'Native American diet' in its home range and was specially honored at the 1912 International Dry Bean Congress for its flavor and reliable yields in rainfed cropping systems (Bhardwaj et al., 2002). However, the spread and development of tepary bean stayed limited to specific forms of dryland farming due to irrigation developments and restricted marketing in the southwestern United States (Porch et al., 2013). It has been receiving increased attention from researchers for adaptability to dry conditions and as a genetic donor to improve drought tolerance in common bean (*Phaseolus vulgaris* L.) (Pratt, 1983; Singh and Munoz, 1999; Rainey and Griffiths, 2005).

On the African continent, tepary bean has been recognized as an important food crop to combat malnutrition and enhance income and livelihoods of resource-limited farmers in many countries, including Kenya and Zimbabwe (Jiri and Mafongoya, 2016). Small farmers in Botswana grow tepary bean for food and utilize the haulms (stems) as feed for animals (Molosiwa et al., 2014).

One of the nutritional feature of all beans is the presence of large amounts of protein and fiber in their seed. Grain of tepary bean has high protein (240 g kg^{-1}) and iron (0.1 g kg^{-1}) concentrations (Bhardwaj and Hamama, 2004). The bean contains 18 g kg^{-1} oil with 330 g kg^{-1} saturated and 670 g kg^{-1} unsaturated fatty acids. Among the unsaturated fatty acids, 240 g kg^{-1} are monounsaturated, and 420 g kg^{-1} are polyunsaturated (Bhardwaj and Hamama, 2005). Apart from its high nutritional value, tepary bean has been reported to have some medicinal value. They possess unique characteristics to combat diabetes and treat the development of cancer (Garcia-Gasca et al., 2002; McCaffrey, 2016).

Tepary bean is a suitable crop for hot and dry environments. It requires a temperature range of 25-35˚C for optimum germination and has a minimum requirement of 8˚C for its vegetative growth (Scully and Waines, 1987; 1988). Miklas et al. (1994) reported a grain yield of 770-1640 kg ha^{-1} across an array of environments in Central America with a precipitation range of 164-396 mm during a growing season and average minimum and maximum temperature ranges of 16.1-22.8˚C and 29.3-32.5˚C, respectively. In addition, tepary bean seems to improve the soil fertility through biological nitrogen fixation (Shisanya, 2002). Bhardwaj et al. (2002) grew tepary bean successfully as a short duration summer crop in rotation with winter wheat in Virginia, which has more humidity and precipitation than the SGP. Markhart (1985) reported that tepary bean tolerates drought better than common bean (*Phaseolus vulgaris* L.) by closing its stomata at a much higher water potential when exposed to water stress. It is found to be highly tolerant of heat, salinity, many diseases, and insects (Miklas et al., 1994; Miklas and Santiago, 1996; Pratt et al., 1990).

Tepary bean has exhibited great potential for forage production, though published literature is limited. Bhardwaj (2013) reported fresh and dry yields of 22.2 Mg ha^{-1} and 4.4 Mg ha^{-1}, respectively, at 59 d after planting on a sandy loam soil in eastern Virginia. Forage quality of tepary bean reported in this study appears to be comparable with alfalfa and soybean forage in terms of CP; however, it had greater fiber concentrations (Table 1.1.).

Tepary bean may fit well within the management systems applied to winter wheat in the SGP due to its drought tolerance and relatively short life cycle of around 60-75 d (Tinsley et al., 1985). The limited amount of information also indicated tepary been might provide much needed nutritious forage during the late-summer period (Bhardwaj, 2013). Grazing or one cutting for hay with subsequent plow down would be a possible method of management. Further, lines that have semi-vine growth forms may also have value as cover crops. However, due to the lack of field studies, more research is required to evaluate its feasibility as a forage crop in the SGP.

1.4. MOTHBEAN

Mothbean [*Vigna aconitifolia* (Jacq.) Marechal] is an annual summer legume, cultivated mainly in the semi-arid and arid regions of India due to its high drought and heat tolerance. Mothbean is a short-duration crop with a 60-75-d lifespan (Kumar and Rodge, 2012). Optimum production can be achieved within a temperature range of 24-32˚C, but mothbean can tolerate daytime temperatures up to 45˚C (Vijendra et al., 2016). Water requirements of mothbean during a growing season are quite low, ranging between 190-260 mm in its native regions (Rao and Poonia, 2011). Singh et al. (2000) estimated an evapotranspiration rate of 1.8-2.2 mm d^{-1} and 4.8 mm d^{-1}, respectively, during early vegetative and reproductive growth stages. Therefore, it has the potential to perform well in environments with low and erratic amounts of rainfall (Narain et al., 2001), which is a regular feature of summer precipitation in the SGP. The wide adaptability of mothbean enables it to grow on sand dunes or other marginal lands with slight salinity and a wide pH (3.5-10) range (Manga et al., 2015; Vijendra et al., 2016).

Mothbean serves as a multipurpose crop in its native range as a source of food, forage, and green manure (Manga et al., 2015). Mothbean seeds are rich in protein (230 g kg^{-1}) and contain some essential amino acids, minerals, carbohydrates, fiber, and vitamins (Siddhuraju et al., 1994; USDA ARS, 2016). Although it is mainly grown in arid or desert regions of India, it seems to be adaptable to a broad range of climatic conditions. Research over 100 y ago (Conner, 1908) reported a yield (fresh weight) of 4.4 Mg ha^{-1} in northwest Texas when planted at a 90-cm row spacing; no seed set was recorded at that location. Kennedy and Madson (1925) reported yields (fresh weight) of 45 Mg ha^{-1} and 60 Mg ha^{-1}, respectively, when planted at 90-cm row spacing under irrigated and dryland conditions near Fresno, CA. The given explanation for greater yield in dryland conditions was good condition of the seed bed at planting which resulted in a better stand than under irrigated conditions. They also reported an average seed yield of 198 kg ha^{-1} from a mothbean study conducted near Davis, CA. Bhardwaj and Hamama (2016) reported seed yields of mothbean varied from 55-468 kg ha^{-1} in a test of 54 accessions in the eastern United States. In central Oklahoma, a preliminary study involving 10 mothbean lines reported a dry forage yield of 7.3-18.1 Mg ha^{-1} and grain yield of 0.1-1.0 Mg ha^{-1} on harvesting moth bean at 100 d after planting (Baath et al., 2018). The same study reported that mothbean forage possessed 110-150 g kg^{-1} CP, 320-420 g kg^{-1} neutral detergent fiber (NDF), 210-300 g kg^{-1} acid detergent fiber (ADF), and 730-840 g kg^{-1} in vitro true digestibility at maturity.

Mothbean could be used to increase the supply and quality of forage in semi-arid and arid regions (National Research Council, 1979). Individual plants have a vining and semi-trailing growth habit which have the potential to cover large areas. As such, this low-growing legume has the potential to cover the soil surface to protect soil moisture, reduce soil temperatures, and decrease soil erosion (Kumar, 2002; Bhardwaj and Hamama, 2016). Since it is a legume, mothbean can also improve soil fertility through nitrogen fixation (Vir and Singh, 2015).

Research on the use of mothbean as forage was initiated during the early 20th century and showed promising results in dry US environments (Conner, 1908; Kennedy and Madsen, 1925). However, the crop was neglected afterwards for unknown reasons. Based on its food and forage potentials, soil covering ability, and short life cycle, mothbean appears to be a candidate for improving not only livestock production systems when grown as a summer crop in rotation with winter wheat but also for increasing agro-ecosystem diversity in the SGP.

1.5. COWPEA

Cowpea [*Vigna unguiculata* (L.) Walp.] is an important herbaceous, warm-season legume that originated and was domesticated in Africa. Cowpea varieties exhibit different growing habits including tall and vine-like, short and bushy, or prostrate. Cowpea plants have leaves with three broad leaflets, white inflorescences and curved pods (Sheahan, 2012). Most cowpea types possess an indeterminate stem and branch apices (Timko et al., 2007). It has a deep tap root which has been measured at a depth of 2.9 m at flowering (Babalola, 1980). It is a valuable food legume and livestock feed in the semi-arid tropics, including regions of Asia, southern Europe, Africa, Central and South America, and the southern United States (Timko and Singh, 2008).

Cowpea is a well-adapted and versatile crop, capable of good yields under high temperature and water deficits (Ehlers and Hall, 1997; Hall et al., 2002). It requires a minimum temperature of 18˚C through all developmental stages (Timko and Singh, 2008; Badiane et al., 2014). Optimum growth occurs at mean daily air temperatures of 28˚C (Craufurd et al., 1997). Cowpea is generally photo insensitive (Davis et al., 1991). It is drought tolerant and can produce a grain yield of about 1.1 Mg ha^{-1}, with rainfall amounts as low as 180 mm during the growing season (Hall and Patel, 1985). However, it does not withstand flooded conditions over long periods (Clark, 2007). Cavalcante et al. (2016) reported water requirements of cowpea ranging from 240-310 mm under semi-arid conditions in Brazil. Cowpea can fix nitrogen and has performed well in sandy (80%), low fertility soils with <0.2% organic matter and low phosphorus (Sanginga et al., 2000).

Cowpea is also shade tolerant, and capable of being intercropped with tall forage crops including sorghum [*Sorghum bicolor* (L.) Moench], maize (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and sugarcane (*Saccharum officinarum* L.; Singh et al., 2003).

Cowpea is an absolute multifunctional crop, since it serves as a highly nutritious food, a forage, and a green manure or cover crop. Cowpea grain has served as a dietary source of protein in areas with low-protein cereal and tuber-based diets. Cowpea seed contains 240 g kg^{-1} protein, 600 g kg^{-1} carbohydrates, 110 g kg^{-1} fiber, 13 g kg^{-1} fat, and considerable amounts of vitamins and minerals (USDA ARS, 2016). It can also be employed as livestock feed (Singh et al., 2006).

Cowpea has the capacity to serve as fodder due to its high biomass yield and forage value. The common name cowpea even originated because of its use as hay for cattle in the United States and other parts of the world (Timko et al., 2007). Cowpea hay plays a critical role in feeding livestock during the dry season in West Africa (Tarawali et al., 1997). In a study on nutritive value of forage conducted in Iran (Dahmardeh et al., 2009), cowpea fodder was shown to have 156-196 g kg^{-1} CP, 497-545 g kg^{-1} NDF, and 293-322 g kg^{-1} ADF. It has a low risk of causing bloat in cattle, although bloat may occur on introducing hungry stock onto the crop (Mullen and Watson, 1999).

Generally, the short duration varieties (about 65-70 d) are grown for grain, while the long duration (110-130 d) varieties are used for forage. Some varieties with medium maturity rates (80-85 d) exist for a dual-purpose role. These varieties yield about 1.5 Mg ha^{-1} grain and 2.5 Mg ha^{-1} haulms, with a CP of 170-180 g kg^{-1} and dry matter digestibility of 640-710 g kg^{-1} (Singh et al., 2003). It is also an excellent cover crop candidate, being fast growing, having a long taproot, and immense vegetative spread

(Sheahan, 2012). About 50 cowpea varieties are commercially grown in the United States in regions extending from the Great Lakes to Florida and from the Atlantic to Pacific coasts (Sheahan, 2012).

Cowpea is one of the few annual legumes besides soybean that has received some degree of research and use in the SGP. Forage cowpea in north-central Texas yielded 0.5-3.2 Mg ha^{-1} dry matter with CP concentrations ranging from 161-208 g kg^{-1} under dryland conditions; both amounts were greater than that of forage soybean (Muir, 2002). Rao and Northup (2009a) reported that cowpea had greater potential as a summer crop for forage or green cover than soybean during dry years in the SGP due to its shorter lifecycle, high N concentrations and forage digestibility. Depending on the management and seasonal circumstances, cowpea can be grazed 8-12 weeks after planting until the leafy portion has been eaten (Mullen and Watson, 1999). Cowpea appears to be another option for producers of the SGP wishing to grow a summer crop to enhance sustainability of rain-fed forage-livestock production systems. The genetic improvements in modern cultivars (Sheahan, 2012), indicates there is need for additional research on the values of cowpea as a summer forage in the SGP.

1.6. MUNGBEAN

Mungbean [*Vigna radiata* (L.) Wilczek.], also known as green gram, is an annual warm-season legume, with a highly branched and upright growth form, and trifoliate leaves. It has a well-developed taproot reaching to a depth of 1.0 m (Sangakkara et al., 2001). It is native to the northeastern Indo-Burma region, and is one of the major food legume crops of Asia (Bhardwaj and Hamama, 2016). Mungbean seeds provide high amounts of easily digestible protein for human consumption (Swaminathan et al., 2012).

Mungbean grain contains 240 g kg^{-1} protein, 15 g kg^{-1} oil, and 50 g kg^{-1} sugars (Bhardwaj and Hamama, 2016). Whole seeds are commonly used to grow bean sprouts for salads or used in soup mixes in the United States.

Mungbean is adaptable and has been cultivated in different parts of world including Southeast Asia, Africa, South America, North America, and Australia. It has a short life cycle, requiring 90-120 frost free days to achieve maturity (Ranawake et al., 2012). Mungbean is commonly grown with daily temperatures ranging from 20-40˚C; the minimum temperature requirement for emergence is 12˚C, and the range of optimum growth is 28-30˚C (Fyfield and Gregory, 1989; Kaur et al., 2015). The total water requirement of mungbean ranges from 440-520 mm under irrigated conditions of northern India (Phogat et al., 1984; Pannu and Singh, 1993). However, mungbean can be grown successfully under lower moisture, rain-fed conditions (Ranawake et al., 2012). It requires guaranteed soil moisture via pre-sowing irrigation or adequate rainfall for better germination and stand establishment (Kumar and Sharma, 2009). Allahmoradi et al. (2011) reported vegetative growth of mungbean was more susceptible to drought stress than reproductive stages. However, Thomas et al. (2004) found mungbean was capable of recovering from drought stress during early development and compensating for yield losses later in the growing season.

The planting and production strategies for mungbean are similar to soybean, so producers in the SGP would not require specialized equipment for planting and grain harvest (Bhardwaj and Hamama, 2015) or different strategies for grazing management. Mungbean plants may have potential as cattle forage due to high digestibility (825 g kg^{-1}) and N concentrations (26 g kg^{-1}) (Rao and Northup, 2009a). Twidwell et al. (1992)

reported CP concentrations of 150-230 g kg^{-1} in mungbean forage. Boe et al. (1991) reported forage yields of 3.75-7.25 Mg ha^{-1} for cultivars of mungbean tested in the northern Great Plains. In comparison, Rao and Northup (2009a) obtained an average forage yield of about 3 Mg ha^{-1} in central Oklahoma in response to a range of different amounts of precipitation during growing seasons. Grazing of mungbean can start six weeks after planting and two grazing periods are obtainable (FAO, 2012). Hay harvests should occur at initiation of flowering for optimum combination of quantity and quality of biomass (Heuze et al., 2013).

Although mungbean has been grown in Oklahoma and Texas in the past, the current level of grain production is low. Most of the US demand for mungbean is met through import, with 15.8 Mg and 16.4 Mg of mungbean and urd beans (*Vigna mungo* L.) being imported in 2015 and 2016, respectively (USDA ERS, 2017b). Such demand shows mungbean grain has US market value and could help increase farmer income in the SGP. This value assumes the development of consumer demand (and marketing mechanisms) that exceeds its value as high quality forage for summer grazing by stocker cattle. Karamany (2006) investigated a dual-purpose approach for mungbean during summers in Egypt. They recorded 5 Mg ha^{-1} of high quality forage (172 g kg^{-1} CP) at harvest of mungbean as hay at 65 d after sowing. These plots were also able to produce an average of 1.5 Mg ha^{-1} seed yield at the end of growing season. The short growing season of mungbean would result in grain harvest by late August in the SGP, which would help conserve soil moisture received in September and October for winter wheat (Rao and Northup. 2009b). Asim et al. (2006) also noted reduced weed, pathogen and pest problems for subsequent wheat crops.

Mungbeans are a potential crop choice to improve productivity of grazing systems, assist in soil moisture conservation, provide reliable economic benefits, and enhance soil fertility. Based on the long-term weather data of the six locations (shown in Figure 1.2., 1.3.), mungbean seems to be a better fit for the eastern sections of the SGP due to greater water needs than other potential summer annual legume crops.

1.7. GUAR

Guar [*Cyamopsis tetragonoloba* (L.) Taub.], also called cluster bean, is a drought tolerant, summer annual legume which is thought to have originated in Africa. It is mainly cultivated in semi-arid zones of northwestern India, Sudan, and Pakistan. There has been some production and genetic development within the southern United States (Stafford, 1982; Reddy and Tammishetti, 2004). India is currently the largest producer (80% of world production) of guar in the world, followed by Pakistan (15%), and the Middle East and African (5%) countries (Gresta et al., 2013). Guar has a single upright main stem (2-3 m) with fine or basal branching stems, trifoliate leaves, 4- to 10-cm long pods with 5 to 12 seeds per pod, and a deep taproot system enabling it to reach moisture below the surface layers of soil (Gresta et al., 2013).

Guar is a shorter-duration crop, requiring 90-120 d to reach maturity, which allows it to fit into different crop rotations (Rao and Northup, 2009a; Rao and Northup, 2013). However, guar is photosensitive, requiring long days for vegetative growth and short days for flowering and pod formation. Seed germination needs temperature within a range of 25-30˚C, and can grow at air temperatures of 35˚C (Singh, 2014). Guar can grow in a wide range of soils, but performs best on fertile, medium textured soils with good drainage. Guar is a drought tolerant crop, delaying growth until moisture is available

(Tripp et al., 1982). As such, guar can grow in areas receiving ≤ 250 mm of annual precipitation (Singla et al., 2016a). Therefore, the environmental conditions of regions where guar is grown in large quantity closely match conditions in the SGP.

Guar has great value in India due to its use to provide multiple products, including forage or feed for cattle, a nutritious vegetable (immature pods) for human consumption, a green manure for soil improvement, and a raw material for several different industries. The grain of guar is a rich source of protein, fiber, minerals (Ca, Fe, and P) and ascorbic acid (Singh, 2014). Guar seeds have numerous industrial uses due to its binding capability and viscosity of the polysaccharide galactomannan (guar gum), which is obtained from the endosperm (Singla et al., 2016a). High-grade guar gum is utilized in food industries, while low-grade gum is used in the textile, paper, and mining industries. Recently, the demand and price of guar gum has increased globally due to its use in oil fracking (Gresta et al., 2013). Within the fracking industry, the largest consumption of guar gum in the world is by US companies, with most of the demand being met through importation (Singh, 2014; Singla et al., 2016b). Therefore, it is primarily grown as a seed crop in the United States. Singla et al. (2016b) reported grain yields of 1.1-1.8 Mg ha $^{-1}$ for eight different varieties evaluated in Las Cruces, New Mexico. Guar also can improve soils through its soil-binding roots and N-fixation, which benefit subsequent crops (Wong et al., 1997). Cotton yields were increased by 15% when grown in rotation with guar (Tripp et al., 1982).

Although guar has been cultivated mainly as a grain crop in the United States, it may also have forage potential, though information on the value of guar as either hay or grazed pasture is mixed. Guar hay was found to be palatable and digestible to livestock in

India (Patnayak et al., 1979). In comparison, Rao and Northup (2013) suggested guar as potential forage for the SGP, and an annual alternative to high water-demanding legumes like alfalfa (*Medico sativa* L.). Rao and Northup (2009a) reported 162-225 g kg^{-1} CP and 606-712 g kg^{-1} IVDDM for forage produced by a grain cultivar 'Kinman' in Oklahoma. Studies in the SGP also suggested that hay may be harvested during vegetative stages of growth, as CP and digestibility were continuously reduced with increasing levels of plant maturity (Rao and Northup, 2009a; 2013). Singla et al. (2016a) reported an average biomass yield of 2.9-3.8 Mg ha^{-1} near Las Cruces, New Mexico. Rao and Northup (2013) reported a forage yield of 4.25-4.75 Mg ha^{-1} for three Indian-origin forage varieties grown in central Oklahoma.

While the value of guar as a hay crop looks promising, there is limited information on its value as grazed pasture, and many reports are anecdotal. The surface of guar leaves is covered in fine hairs, which were thought to hinder grazing in India. However, there has been little research on the interaction between guar and grazing animals. Such information is important for defining the suitability of guar as forage or hay. Further research is also needed to ascertain more reliable forage type cultivars, their performance and quality attributes, and best management practices for the variable environment of the SGP.

1.8. PIGEON PEA

Pigeon pea [*Cajanus cajan* (L.) Millsp.], also known as red gram, is a legume from the rainfed tropics and subtropics which has a substantial shrub-type growth form (Singh and Oswalt, 1992). Pigeon pea originated and was domesticated in India. Plants of pigeon pea have erect, woody, pubescent stems of 1-4 m height, alternate trifoliate leaves, papallionaceous (butterfly-shaped) and yellow flowers organized in racemes, and pubescent pods that form at the axils of branches. Pigeon pea has a strong taproot, which can extend to a depth over 2 m (Singh and Oswalt, 1992).

There is a wide range of genetic materials for this legume, and cultivars with a broad range of length of growing seasons exist (Mallikarjuna et al., 2011). In its native range, there are perennial cultivars which can be grown for 3-5 y. However, mostly annual cultivars are preferred for seed production in tropical and subtropical regions (Singh and Oswalt, 1992; Mallikarjuna et al., 2011). Short duration cultivars have been developed that are capable of grain production in the southern United States (Phatak et al., 1993; Yu et al., 2014), and such materials were tested in the SGP (Rao et al., 2002; 2003). Pigeon pea contributed 6% of the total worldwide production of pulse crops in 2014 (FAOSTAT, 2017). Pigeon pea reaches maturity within a range of 120-210 d depending on the cultivar type, location, and sowing time. Rao et al. (2003) observed short-duration (110-140 d) US varieties reached physiological maturity 118 d after planting in the SGP. Pigeon pea is a short-day plant and requires an optimum temperature between 20-24˚C for development (McPherson et al., 1985; Carberry et al., 2001).

Pigeon pea can grow in soil types ranging from sand to heavy clay loams. The water requirements of pigeon pea in India ranged between 200-240 mm when grown during summer (Mahalakshmi et al., 2011). Limited accounts are available on water use by pigeon pea, however it has remarkable drought tolerance due to its deep roots and ability to undergo osmotic adjustment in its leaves (Subbarao et al., 2000). Although pigeon pea is mainly grown under rainfed conditions, it is affected by intensity and timing of rainfall. Yu et al. (2014) in west-central Tennessee found 172% greater seed yield in a year receiving normal rainfall combined with drought during the early growing season compared to a year receiving heavy rainfall during early growing season and severe drought at flowering. Similar responses to different rainfall patterns occurred in central Oklahoma (Rao and Northup, 2009b). Pigeon pea was also noted to have higher water use efficiencies under dry conditions compared to wet growing conditions (Yu et al., 2014).

Pigeon pea has been used as a true multi-purpose crop in India and Africa, with the entire plant used to supply human and livestock feedstuffs, enhance soil fertility, and supply fuel for cooking fires (Singh and Oswalt, 1992). The raw mature seeds contain 193 g kg^{-1} protein, 627 g kg^{-1} carbohydrates, 64 g kg^{-1} fiber, 20 g kg^{-1} sugars and are a rich source of dietary minerals such as P, K, Mg, Ca, and Fe (Singh and Singh, 1992). The demand for pigeon pea seeds has increased during the last few years due to US immigration from countries where pigeon pea has been grown for grain or vegetable (immature pods).

Leaves and pods of pigeon pea are widely used as livestock forage due to high amounts of protein and palatability. Rao et al. (2003) reported average CP concentration and IVDDM of 212 g kg^{-1} and 758 g kg^{-1}, respectively, for leaves, which was similar to alfalfa. However, the stems were low in CP (56 g kg^{-1}) and digestibility (420 g kg^{-1}), which lessens the overall forage value for the entire plant. Foster et al. (2009) reported pigeon pea raised in Florida contained 121 g kg^{-1} CP, 695 g kg^{-1} NDF, and 689 g kg^{-1} IVDMD at final harvest. Rao and Northup (2012) noticed that cattle did not selectively graze primary and secondary stems of pigeon pea during a grazing trial, likely due to high lignin content and low digestibility. A later trial in Oklahoma recorded higher amounts of tannins in the stems of pigeon pea than in leaves (B. Northup, unpublished data). The by-products of split seeds for human consumption can provide a low cost source of protein for animals compared to other sources of feed supplements such as fish and bone meal (Phatak et al., 1993).

The value of pigeon pea grown for grain and forage has been researched in Tennessee, Florida, Virginia, and Oklahoma. Results showed some degree of adaptation of pigeon pea in these different regions. Low water requirements and high drought tolerance indicates that pigeon pea would fit as a multi-purpose summer crop for the SGP. Early-maturing varieties have the potential to provide grain and sufficient herbage of moderate nutritive value for grazing. Rao and Northup (2012) observed animal gains of 140 kg ha^{-1} and average daily gain of 1.0 kg during late August through early September grazing bouts, compared to 0.5-0.75 kg d^{-1} gain for warm-season grasses. However, there is need to develop new cultivars with greater leaf-to-stem ratios and finer stems to provide greater amounts of high nutritive value forage and allow longer grazing periods. In addition, systems-level water, nutrient, and economic budgets need to be evaluated so producers can make informed decisions regarding the use of wheat-pigeon pea rotations in the SGP.

1.9. FINGER MILLET

Finger millet (*Eluesine coracana* Gaertn L.) is an erect, tufted, annual grass that originated in the Ethiopian and African highlands which belongs to the Chloridoideae subfamily. The inflorescence appears like fingers on a hand, thus resulting in the common name “finger millet” (Dida and Devos, 2006). It is also known by other names such as ragi (India), kaddo (Nepal), fingerhirse (Germany), koracan (France), bulo (Uganda), wimbi (Kenya), and barankiya (Ethopia).

Finger millet is an important crop in many drought-prone regions of the world due to its ability to grow in adverse conditions, and on marginal or poor soils (Dass et al., 2013). It has a wide adaptability to growing conditions and is extensively cultivated in India, Nepal, Myanmar, China, Sri Lanka, and Japan in Asia, and Kenya, Uganda, Ethiopia, Zaire, Tanzania, Somalia, and Rwanda in Africa (Upadhyaya et al., 2010). Finger millet has a strong adventitious root system, which consists of a thick crown with fibrous lateral roots at the shoot base (Mackey et al., 2005; Goron et al., 2015). It is adaptable to a range of agro-climatic conditions. However, it grows best in warm conditions with average air temperatures between 26-29˚C. A minimum of 8-10˚C is required for germination and grain yield is reduced if the average temperature falls below 20˚C (Gangaiah and Gautam, 2008).

Finger millet is a short day plant, requiring an optimum photoperiod of 12 hours (Mackey et al., 2005). It has a 100-130 days' maturation period and GDD requirements in the range of 1860-2060˚C with a T_{base} of 10˚C to attain maturity (Revathi and Rekha, 2017). Finger millet can tolerate drought and has a low water requirement (~325 mm) to complete its life cycle (Rajegowda et al., 2015). Finger millet has generated grain yields of 1-1.5 Mg ha^{-1} and forage yields of 3 to 9 Mg ha^{-1} under rainfed conditions in India (Gangaiah and Gautam, 2008). Finger millet was also found to be water use efficient under irrigated conditions, with 10-20% lower water consumption compared to sorghum (Kissan, 2006). The crop can also withstand some water logging or salinity, but is highly sensitive to frost (Kono et al., 1988; Satish et al., 2016; Mackey et al., 2005). It can be grown in soils with pH ranging from 4.5 to 7.5 (Gangaiah and Gautam, 2008).

Finger millet has served as a safeguard against malnutrition during drought and is a staple food in some regions of India, and eastern and central Africa (Singh and Raghuvanshi, 2012). It is utilized in many ways including bread (roti), porridge, malt, popped products and in both alcoholic and non-alcoholic brewing industries (Shobana et al., 2013; Upadhyaya et al., 2006). Finger millet grain contains 7-14% protein, 73% carbohydrate, 1.5% fat, and 3.6% fiber. The seed is also higher in Ca, P, Fe, and Mn than other cereal grains (Dida and Devos, 2006) and is considered an ideal food for breast-feeding mothers, growing children, and the infirmed (National Academy of Sciences /National Research Council, 1996). Kumari and Sumathi (2002) reported the grain of finger millet is useful in controlling blood glucose levels and recommended it for diabetic patients.

Finger millet silage/straw is highly nutritious and fed to livestock in several African and Asian countries (Upadhyaya et al., 2006; Sumathi et al., 2005). Gowda et al. (2015) reported nutrient concentrations of CP (14.6%), Ca (1.29%), P (0.50%), and K (5.08%) levels in forage of finger millet accessions grown in the semi-arid Texas High Plains that were higher than forage of corn and forage sorghum. Due to its strong adventitious root system, it can also be an effective cover crop (Samarajeewa et al., 2006).

Despite its merits, finger millet is widely neglected scientifically and in international use. Most of the available research has been conducted in India and has primarily focused on the nutritional properties of grain compared to other crops. In the

U.S., Gowda et al. (2015) reported promising research results when testing five accessions of finger millet under irrigated conditions in the Southern High Plains. However, there could be an issue with grain production due to photoperiod sensitivity in the SGP as was noticed in central California and the Texas Panhandle (National Academy of Sciences/ National Research Council, 1996; P. H. Gowda, personal communication, 2017). Based on its merits, there is a fundamental need to evaluate various photo insensitive varieties to determine their climate adaptability, drought tolerance, yield capabilities, and their nutritional quality in order to assess the potential of finger millets as both summer forage and grain crop for the SGP.

1.10. TEFF

Teff (*Eragrostis tef* [Zucc.] Trotter) is a warm season, tufted, annual, C_4 grass that that is native to Ethiopia and Eritrea. The name teff means "lost" which relates to its tiny seed (1-1.5 mm long), which is lost easily if dropped on the ground (Davison and Laca, 2010). Teff has a large crown with several tillers, an open panicle inflorescence, and a shallow fibrous root system (Roseberg et al., 2006). Araya et al. (2011) reported a maximum rooting depth of 30 cm in a silty clay soil. Teff has a short life cycle of 90 to 100 days (Girma, 2008). Teff is considered drought tolerant once established, and unlike other cereals, can provide reasonable yields under low moisture conditions (Phanacharoensawad, 2009). Moreover, teff grows well in Vertisols which are normally water logged with occurrence of high precipitation (Reinert et al., 2012).

Farmers in Ethiopia generally broadcast teff seeds on the soil surface and lightly incorporate the seed into the soil. However, seeding depth is critical in planting teff with mechanized systems to attain good emergence. Evert et al. (2009) found more emergence of teff at depths of 0.6 and 1.3 cm than at the soil surface or 2.5 cm deep. Teff grows within a temperature range of 10-30˚C and 430 to 560 mm rainfall during growing seasons in Africa (Hunter et al., 2007). However, it can grow in any climate (Cheng et al., 2015), provided the minimum soil temperature at planting is above 18.4˚C; cooler soil temperatures inhibit germination (Miller, 2010a; Stalknecht, 1993). Evert et al. (2009) noted that soil temperatures below 19˚C slowed emergence but did not affect final stands in a growth chamber experiment.

Teff grows vigorously if daytime temperatures lie in a range of 27-32˚C (Roseberg et al., 2006). Teff is a short day length plant that is traditionally grown in Ethiopia under a photoperiod of 11-13 h. van Delden et al. (2012) reported a delay in heading time but more biomass production with increases in day length to 13.5-16.5 h. According to a study conducted by Araya et al. (2010) in Ethiopia, teff required 338 mm of total water during the growing season, which is lower than requirements for winter wheat in the SGP (Patrignani et al., 2014). Further, Araya et al. (2010) proposed growing teff for biomass under deficit irrigation, or without supplementary irrigation, in northern Ethiopia with 184-278 mm precipitation received during the growing season (June to September). Weed control, especially grasses, is critical during the early growth stages to achieve high yields (Marsalis and Lauriault, 2015).

Teff is mainly grown as a cereal crop in Africa, and provides over two-thirds of the grain needs of the population of Ethiopia (Degu et al., 2008). Teff grain is consumed as a flour, porridge, beer, thickener for soups, gravies, stews, puddings, and in making grain burgers (Phanacharoenasawad, 2009). Teff grain contains high level of the minerals Ca, P, Fe, Mg, and the vitamin thiamine (Reinert et al., 2012). Teff grain is also a good source of protein (11%), carbohydrate (80%), fat (3%), fiber, and the amino acid lysine, which is deficient in other grain cereals (Girma, 2008). Teff grain has low gluten content and was introduced as a niche crop in the US for people suffering from Celiac's (gluten intolerance) disease (Miller, 2010). Araya et al. (2011) reported a range of grain yields of 50-210 kg ha^{-1} in northern Ethiopia.

Teff has recently gained popularity as alternative summer forage by both producers and researchers in the southern and western U.S. It is fine stemmed, palatable, and preferred by livestock over other grass hays (Miller, 2010). Teff grows rapidly and can provide high yields at first cut in 50 to 55 days (Hunter et al., 2007). Forage yields by teff have ranged from 6.5-23.5 Mg ha^{-1} in the western US depending upon location, cutting plan, duration of growing season, water availability and amounts of applied fertilizers (Lemus and White, 2016; Davison et al., 2011; Norberg et al., 2008). Forage quality of teff was reported as similar to timothy hay in terms of CP, fiber, and nutrient concentrations. The fast and heavy growth of teff aids in competiveness and can make good hay or silage for horses and cattle (Miller, 2010). The fibrous root system of teff makes it a potentially useful cover or green manure crop. However, the shallow root system means teff plants can be easily pulled from the soil by grazing livestock.

Teff has been assessed in 24 states of the U.S. and was shown to have a broad potential range of geographic adaptation (Miller, 2010). However, there are few accounts available reporting the performance of teff, its water use efficiency productivity in dry land systems, or in rotation with winter-wheat. As a C_4 plant, teff could be a promising forage crop under the hot and limited soil moisture conditions of summers in the SGP.

However, there is need to explore its climate adaptation, cultivar performance, and test its compatibility within continuous rotations of winter-wheat.

1.11. CONCLUSION

Many of the above discussed grain crops could have some potential to aid in filling the slump in forage quality that normally occurs during the mid to late-summer period in the SGP (Table 1.1.). Both tepary bean and mothbean were known for their remarkable drought tolerance in the early 20th century, but were neglected afterwards. They are likely to be valuable in rainfed systems in the SGP, due to their excellent soil covering ability and heat and drought tolerance. There is a need to evaluate the capacity of cultivars of these two species from different regions of the world to examine their adaptability to the varied growing conditions that exist in the SGP.

Cowpea has been a commonly used summer cover crop by producers in the drier regions of Oklahoma and Texas where other legumes rarely succeed. Mungbean has also shown high forage yields and nutritive value, but is less drought-tolerant than cowpea. Thus, mungbean may fit well in eastern parts of SGP which receive more precipitation during summer. The US grain market for both cowpea and mungbean crops is expanding due to increasing Asian and African populations and shifts in dietary preferences. Therefore, their grain production may also provide some potential for producers to generate improved cost-benefit ratios.

Seed of guar is also in high demand due to their industrial uses, but the nutritive value of guar forage declines with maturity. There would be tradeoffs between the values of grain crops and forage value of guar if producers chose harvesting hay at maturity. Studies involving overall economic analysis of animal gain and grain production can bring more insight on value of guar in SGP. Pigeon pea has shown its ability to produce grain and forage with moderate nutritive value that supports animal gain compared to traditional warm-season grasses. However, developing new cultivars with greater leaf-to-stem ratios can further improve nutritive value and allow lengthier grazing periods.

Both finger millet and teff, being C_4 species, have potential to provide high forage yields, compared to other warm-season grasses in SGP. Teff has shown great adaptability across many parts of the U.S. and could perform well in SGP. In contrast, the function of finger millet as either grain or forage crop in the SGP is unknown. Studies evaluating their adaptability, yield and quality, and economic performance are needed to describe the applicability of these grasses as summer crops for the SGP.

In general, all of the discussed crops show potential of use as components of different strategies to increase precipitation use efficiency, minimize soil erosion, meet nitrogen requirements (legumes) for following crops, and build organic matter and soil structure. Examination of management practices to define best practices for growing these novel crops, and their comparison to more commonly used pulses are required. Further, systems-level water, nutrient, and economic impacts of growing these crops in rotation with winter wheat need to be evaluated for optimal enhancement and improved overall effectiveness of forage-stocker systems.

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Table 1.1. Characteristics of annual crops grown in different regions of the world with potential for the summer growing season.

		Growing conditions					**Forage quality**			
Crop	**Native range**	**Growing climate**	**Optimum temperature**	**Water required**	**Growing Season**	**Livestock feed**	**CP**	**IVDDM**	**Forage yield**	**Grain yield**
			(˚C)	**(mm)**	**(days)**		**(g kg^{-1})**	**(g kg^{-1})**	**(Mg ha^{-1})**	**(Mg ha^{-1})**
Soybean	China	Sub-humid	25-30	420-540	100-120	Hay/graze	150-190	740-790	1.1-5.2	0.3-1.5
Tepary bean	NW Mexico and SW US	Arid	25-35	NA	60-75	Hay/graze	210	n/a	4.4	0.8-1.6
Mothbean	India	Arid	24-32	190-260	60-75	Hay/graze	110-150	730-840	7.1-18.1	0.1-1.0
Cowpea	Africa	Semi-arid	28	240-315	65-70	Hay/graze	160-210	640-710	0.5-3.2	1.5
Guar	Africa	Semi-arid	25-35	250	90-120	Hay	160-220	610-710	2.9-4.7	1.1-1.8
Mungbean	Indo-Burma	Sub-humid	28-30	440-520	90-120	Hay/graze	150-230	825	3-7.5	1.5
Pigeon pea	India	Semi-arid	20-24	200-240	110-140	Graze/seeds as feed	121	689	3-9	1.2-5.4
Finger millet	Africa	Semi-arid	20-29	325	100-130	Silage/straw /hay	146	n/a	3-9	1.0-1.5
Teff	Ethiopia	Semi-arid	27-32	340	90-100	Hay/silage	90-140	n/a	6.5-23.5	0.1-0.2

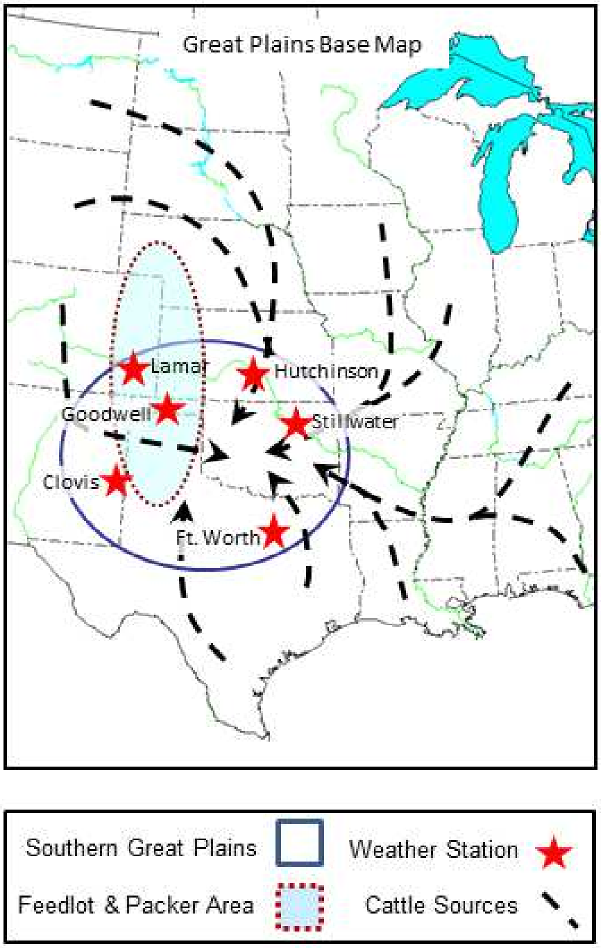

Figure 1.1. Location of the southern Great Plains (SGP), sources of cattle that graze in the region in route to feedlots, and the area with large concentration of feedlots and co-located packers.

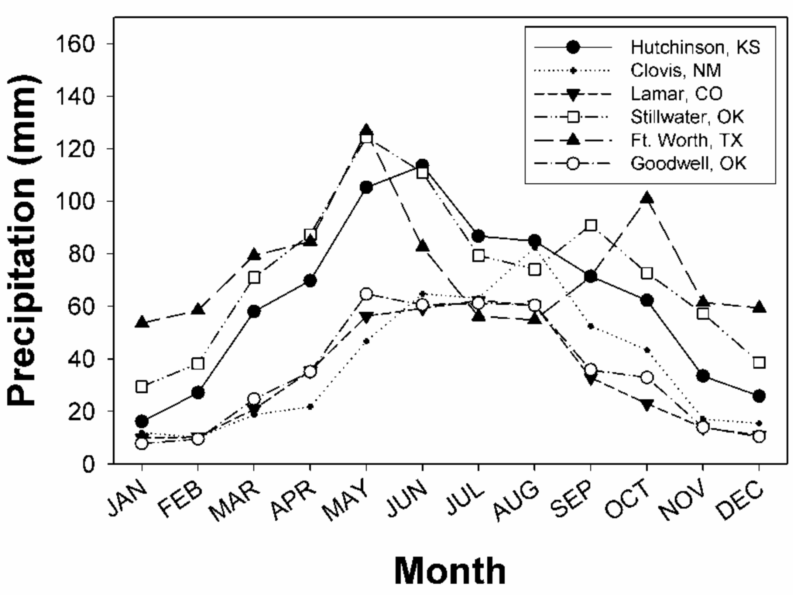

Figure 1.2. Long term (1966-2016) average monthly precipitation for six locations within the US Southern Great Plains (SGP).

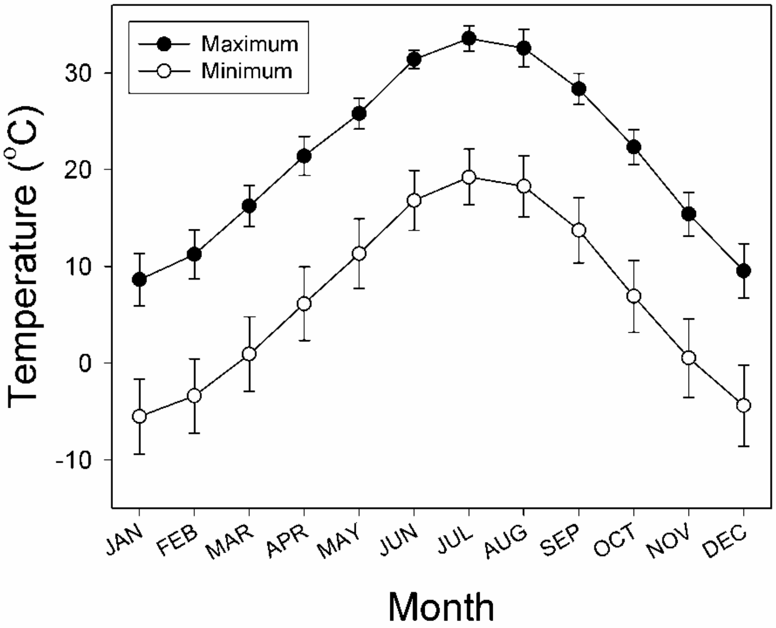

Figure 1.3. Long term (1966-2016) average monthly maximum and minimum air temperatures of six locations within the US Southern Great Plains (SGP). Error bars indicate standard deviation.

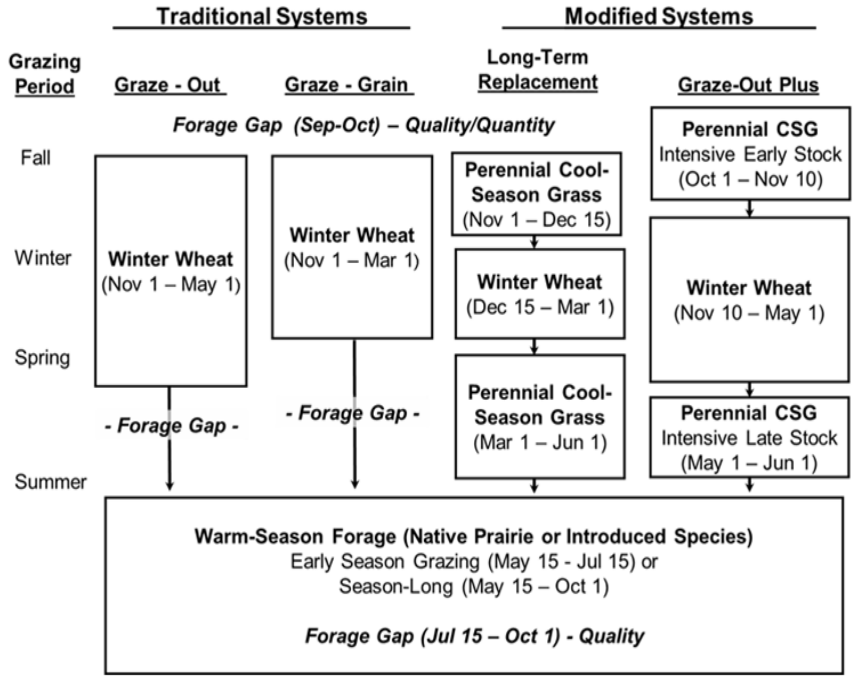

Figure 1.4. Gaps in available traditional winter wheat-summer forage systems in the SGP.

CHAPTER II

FORAGE POTENTIAL OF TEPARY BEAN AND GUAR IN THE SOUTHERN GREAT PLAINS

ABSTRACT

Low nutritive value of perennial warm-season grasses often causes limitation to stocker cattle production in the U.S. Southern Great Plains (SGP). Exploration of novel legumes capable of generating nutritious summer forage is required to fill forage deficit periods. This two-year field experiment compared the seasonal changes in forage biomass, leaf-to-stem ratio, and chemical composition of three varieties each of tepary bean [*Phaseolus acutifolius* (A.) Gray] and guar [*Cyamopsis tetragonoloba* (L.) Taub.] to soybean [*Glycine max* (L.) Merr.]. Tepary bean cv. Black outperformed soybean and guar varieties by producing 18-48% greater aboveground dry matter (ADM) amounts (6537 kg ha^{-1}) with a leaf-to-stem ratio of 3.1 at 65 days after planting (DAP). The ADM and leaf nutritive value of soybean were not surpassed by the other five tested legumes, but had the least digestible stems with an in vitro true digestibility (IVTD) of 529-581 g kg^{-1} in both years. Guar varieties maintained a lower leaf-to-stem ratio (1.3-1.5 kg kg^{-1}) throughout the growing season, which could limit its value for grazing compared to other legumes. We concluded tepary bean could serve as an alternate forage option to soybean

for producers in the SGP. Tepary bean possessed the greatest capabilities for producing adequate biomass yields with superior and consistent nutritive value when grown as a summer forage. Future research should focus on defining management practices for growing tepary bean in extensive production settings for grazing or hay.

2.1. INTRODUCTION

The beef production system in the U.S. Southern Great Plains (SGP) contribute significantly to regional, national, and global food security. A majority of weaned calves produced through cow-calf operations in the United States are eventually feedlot finished in the SGP (Baath et al., 2018a). However, there is inadequate feedlot space to annually accommodate all these animals simultaneously. Therefore, large numbers of animals remain as stockers grazing on available pasturelands in the SGP, to generate low costgain until space becomes available (Peel, 2003). Kansas, Oklahoma, and Texas represent most of the SGP, and are ranked among the top five beef-producing states, which highlights the significance of the region to the US beef industry (USDA-NASS, 2018).

In the SGP, stocker cattle mainly rely on pastures of winter wheat or other cool-season grasses from fall through early spring, and perennial warm-season grasses during late spring and summer (Coleman and Forbes, 1998). Although these forage resources allow grazing throughout the year, there are gaps when forage yield and nutritive values limit rates of weight gain by stockers (Baath et al., 2018b). The most common and important issue is the reduction in nutritive value of perennial warm-season grasses in later cuts during mid-July through September, which demands protein supplementation to achieving acceptable animal gains. (Philips and Coleman, 1995; NRC, 1996). Therefore, one possible solution is to find alternate summer crops capable of producing nutritious forage to improve the performance of stocker cattle during late-summer, and enhance the overall sustainability of forage-stocker systems in the SGP. The capacity of potential forages to generate sufficient biomass under limited soil moisture will be particularly critical, given the variability associated with amount and timing of precipitation in the SGP (Patrignani et al., 2014; Singh et al., 2019).

Several grain legumes may have the capability to produce high-quality forage and feed for livestock with limited amounts of soil moisture, and provide ecosystem benefits such as higher soil organic N levels, run-off and soil erosion reduction, higher carbon sequestration, and mitigation of greenhouse gas emissions (Stagnari et al., 2017). Furthermore, the continual rise in prices of inorganic nitrogen fertilizers has encouraged producers to include annual legumes into many U.S. cropping systems as forage, grain, or green cover. Ongoing research over the last two decades in the SGP have examined the forage and grain potential of a series of warm-season legumes (Rao et al., 2002; Rao and Northup, 2009,12,13; Northup and Rao, 2015; Baath et al., 2018c). Some legume species, such as pigeon pea [*Cajanus cajan* (L.) Millsp.], could generate high N forage; however, the large proportion of less-digestible stems in biomass was noted to cause limitations for grazing (Rao and Northup, 2012). Such issues have resulted in additional surveys of other legumes from the worldwide pool, to identify novel species and their varieties that may have better forage characteristics and ability to serve as high-quality summer forage.

Tepary bean [*Phaseolus acutifolius* (A.) Gray] is an annual legume that may have some potential to serve as summer forage for stockers. Tepary bean, originated from northwestern Mexico and the southwestern United States, possesses either bush or semi-vine type growing habits with pointed trifoliate leaves, which makes it an excellent cover (Baath et al., 2018a). It is recognized as a food crop in many African countries, including Zimbabwe and Kenya (Jiri and Mafongoya, 2016). Tepary bean is a well-adapted crop capable of producing significant biomass yields with fine stems, and can grow under conditions of high temperatures and extreme water deficits (G. Baath, unpublished data, 2019). An evaluation of tepary bean in eastern Virginia (Bhardwaj, 2013) reported a biomass yields of 4.4 Mg ha^{-1} with 214 g kg^{-1} crude protein (CP), 375 g kg^{-1} acid detergent fiber (ADF), and 411 g kg^{-1} neutral detergent fiber (NDF), when harvested at 59 days after planting (DAP). Based on its drought tolerance, soil covering ability, and the limited information on nutritive value and productivity, tepary bean appears to be a candidate capable of production nutritious forage for stockers. However, field evaluations of tepary bean is necessary to determine its feasibility as a summer forage in the SGP.

Guar [*Cyamopsis tetragonoloba* (L.) Taub.] is another drought-tolerant, multi-purpose legume known for its range of industrial uses (Singla et al., 2016). Past research conducted in SGP suggested that different guar cultivars were capable of generating high N (325 g kg^{-1}), digestible biomass if harvested during vegetative growth (Rao and Northup, 2013). There have been significant genetic improvements in modern guar cultivars within the United States, however, no additional research evaluating their performance in the SGP was performed.

The objective of this field experiment was to quantify and compare seasonal changes in forage biomass, leaf-to-stem ratio, and chemical composition of tepary bean and guar. The hypothesis was that the productivity, leaf-to-stem ratios, and chemical composition of forage produced by a series of tepary bean and guar varieties would not differ from the performance of soybean [*Glycine max* (L.) Merr.].

2.2. MATERIALS AND METHODS

2.2.1. Experimental site

The experiment was conducted during the summer seasons (June through August) of 2017 and 2018 at the USDA-ARS Grazinglands Research Laboratory (35.57 °N, 98.03 °W, elevation 414 m) near El Reno, OK. Two different sites were treated as blocks in the experiment. The soil on one experimental site was classified as Brewer silty clay loam (fine, mixed, superactive, thermic Udertic Argiustolls) with 0-1% slope and a neutral pH of 6.9. The second site has soil characterized as Norge silt loam (fine-silty, mixed, active, thermic Udic Paleustolls) with 3-5% slope and a pH of 5.9 (USDA-NRCS, 1999). Daily maximum and minimum temperatures, and precipitation were acquired from a nearby Oklahoma Mesonet Station (Table 2.1.; http;//mesonet.org/, accessed October 24, 2019). Both experimental field sites were within 1.2-2.0 km radius of the station.

2.2.2. Agronomic Management

The experimental plots were disked twice, rototilled, and culti-packed before planting in both years. The seed of three tepary bean varieties: Black (cv. PT082), Sacaton Brown (cv. PT004) and Sacaton White (cv. PT005) were obtained from *Native Seeds*, Tucson, AZ, and three guar cultivars: Judd69, Matador and Monument were obtained from *Guar Resources*, Brownfield, TX. A soybean variety of maturity group III (cv. Midland 3926 NR2) was included as a control in the study. The seven species-cultivar combinations will be termed as legumes throughout the paper. The experimental design consisted of two replicate blocks (sites), and each of the seven legumes was randomly assigned to two plots per block. Seeds were inoculated (*Bradyrhizobium japonicum* for soybean; cowpea-type *Rhizobium* spp. for tepary bean and guar) and planted 2 cm deep at 40-cm row spacing in four replicate, 5 x 5 m plots. Planting was undertaken on 12 June in 2017 and 11 June in 2018, to match inclusion of the legumes in rotation with crops of winter wheat (Rao and Northup, 2009; Northup and Rao, 2015). Seeding rates were adjusted to attain a planting rate of 10 seeds m^{-1} row. Dry granular fertilizer 18-46-0 was incorporated at the rate of 70 kg ha^{-1} and 100 kg ha^{-1} in 2017 and 2018, respectively. Grass weeds were controlled by herbicide application of Clethodim 2E, and broadleaf weeds were removed through hand weeding at 30 DAP.

2.2.3. Data Collection

Biomass samples were collected on five sampling dates, from 35 to 90 DAP at a bi-weekly interval. Aboveground biomass was collected on each sampling date by clipping randomly selected, 0.5 m row lengths from each plot. Areas previously sampled were avoided in later sampling dates. Each biomass sample was partitioned into leaves (include petioles) and stems, and oven-dried until constant weight at 65 °C to determine the leaf-to-stem ratio. The total of dry weights of fractioned leaves, stems, and pods (when encountered) was identified as aboveground dry matter (ADM). Each leaf and stem sample was ground to 2-mm particle size in a Willey mill for lab analysis. Total N concentration was determined using an auto-analyzer (Model Vario Macro, Elementar Americas, Inc., Mt. Laurel, NJ, USA). The concentrations of NDF and ADF in each sample were determined in accordance with the procedures defined for a batch fiber analyzer, and in vitro true digestibility (IVTD) was obtained by using techniques for a Daisy Digester (ANKOM Technology, Macedon, NY, USA).

2.2.4. Statistical Analysis

The ADM and leaf-to-stem ratio data were subjected to logarithmic and square root transformation, respectively, to correct their non-normal distribution in original scales (Steel and Torrie, 1980). Data were analyzed as a randomized complete block design with repeated measures using PROC MIXED procedure in SAS 9.4. Blocks were considered as random elements, while legume treatment and year served as main fixed effects within the model. Sampling dates (or DAP) were treated as repeated elements, and individual plots were taken as subjects to order analyses. Compound symmetry covariance structures were used to account for covariance and autocorrelation among sampling dates (Littell et al., 1996; Moser and Macchiavelli, 2002). Analyses of variance were limited to two-way interactions among fixed and repeated factors, as there was inadequate degree of freedom ($n = 280$) to test other interactions. The PDIFF procedure of LSMEANS was used to test differences among significant main and interaction effects. Means and mean separation letters were assigned using the PDMIX800 macro (Saxton, 1998). Means for biomass and leaf-to-stem ratio were presented in their original scales following back-transformation (Steel and Torrie, 1980).

2.3. RESULTS

2.3.1. Environmental Conditions

During the summer seasons (June-September) of 2017 and 2018, average monthly air temperatures approximated historical averages, except for a slightly hotter month in

June 2018 and a colder month in August 2017 (Table 2.1.). The amounts of precipitation received during the growing seasons of 2017 and 2018 were 320 mm and 325 mm, respectively, which were 24% higher than the long-term average. However, the timing of precipitation varied within the two growing seasons. Early drought was encountered in 2017, with only 70 mm received during the initial seven weeks of the growing season, and the majority of precipitation (about 80%) occurred in August. In contrast, the precipitation received during 2018 was relatively uniform during the growing season, with 126 mm received in the first seven weeks.

2.3.2. Biomass

Significant legume × DAP ($F_{24,231} = 5.17$; $P < 0.01$) and legume × year ($F_{6,231} = 10.41$; $P < 0.01$) interactions were observed in ADM (Table 2.1.). The lowest amounts of ADM in the legume × DAP interaction were recorded for guar cv. Monument (837 kg ha^{-1}) at 35 DAP, which was not different from guar cv. Matador (Fig. 2.1A). The greatest amounts were produced by tepary bean cv. Brown Sacaton (8130 kg ha^{-1}) at 90 DAP, which was not different from guar cv. Judd69 for that sampling date. Tepary bean cv. Black showed the greatest rate of ADM accumulation (162 kg ha^{-1} d^{-1}) from 35 through 65 DAP, and was consistently higher at 35-50 DAP, producing the greatest amount of ADM (6537 kg ha^{-1}) at 65 DAP among the seven legumes. In comparison to soybean (control), tepary bean cv. Black produced 25% and 36% greater ADM at 50 and 65 DAP, respectively. Moreover, ADM production by tepary bean cv. Black at 65 DAP was not surpassed by the other legumes by the end of growing seasons at 80 DAP. The lowest rate of biomass accumulation was generated by guar cv. Judd69 (77 kg ha^{-1} d^{-1}) between 35 and 65 DAP, which was 57% less biomass than soybean at 65 DAP.

The greatest amounts of ADM production in the legume × year interaction were noted for tepary bean cv. Black (5270 kg ha^{-1}) during 2018 (Figure 2.1B), while the lowest ADM amounts were generated by all three guar varieties (2820-3010 kg ha^{-1}) during the same year. Tepary bean cv. Black was also produced the greatest amounts of ADM during 2017, followed closely by tepary bean cv. White Sacaton and guar cv. Matador. The ADM production by soybean and tepary bean cv. White Sacaton were more consistent in both years, with average ranges between 3780-4290 kg ha^{-1}.

2.3.3. Leaf-to-stem ratio

Legume × DAP ($F_{24,231} = 5.17$; $P < 0.01$) and legume × year interactions ($F_{24,231} = 5.17$; $P < 0.01$) were noted for leaf-to-stem ratios in ADM (Table 2.2.). The highest leaf-to-stem ratios in the DAP × legume interaction were recorded for tepary bean cv. Brown Sacaton (5.1 kg kg^{-1}) and tepary bean cv. Black (4.9 kg kg^{-1}) at 35 DAP, while the lowest ratios occurred in all three guar varieties (0.6-0.8 kg kg^{-1}) at final harvest (Figure 2.2A). Tepary bean cv. Brown Sacaton had the greatest leaf-to-stem ratios until 50 DAP, and remained similar to soybean thereafter. Tepary bean cv. Black consistently maintained higher leaf-to-stem ratios compared to soybean and guar varieties throughout the growing season except at final harvest (90 DAP). This cultivar possessed 19%, 42% and 34% higher leaf-to-stem ratios than soybean at 50, 65 and 80 DAP, respectively. In contrast, though there was no overall trend within the three guar varieties, this group generated consistently lower leaf-to-stem ratios among the seven tested legumes.

Within the legume x year interaction, tepary bean cv. Black and tepary bean cv. Brown Sacaton maintained overall higher leaf-to-stem ratios (2.7-2.9 kg kg^{-1}) in both years, but they were not significantly different ($P > 0.05$) from soybean in 2017 (Figure 2.2B). Guar cv. Matador responded differently year-wise and had lower leaf-to-stem ratios in 2017 as compared to 2018.

2.3.4. Leaf nutritive values

Significant legume ($F_{6,5.99} = 6.38$; $P < 0.05$) and DAP ($F_{4,230} = 88.48$; $P < 0.01$) main effects in leaf N concentrations were observed (Table 2.2), while interactions among legumes, DAP and years were not ($P > 0.05$). The leaf N concentrations of the tested legumes ranged from 32.6 to 38.1 g kg^{-1} (Figure 2.3A). Among legumes, guar cv. Judd69 had the greatest N concentration in leaf biomass (38.1 g kg^{-1}), while the lowest concentration (32.6 g kg^{-1}) was reported for tepary bean cv. Brown Sacaton. The other legumes exhibited similar leaf N concentrations. Nitrogen concentrations in leaf biomass in all legumes were affected by maturity, and a significant cubic response ($P < 0.01$) was observed against DAP (Figure 2.3B). Within growing seasons, the greatest amounts of leaf N (46.7 g kg^{-1}) were accumulated on 35 DAP, while the lowest amounts (28.1 g kg^{-1}) were recorded on 90 DAP.

Tests on IVTD concentrations in leaf biomass showed significant legume × DAP ($F_{24,230} = 3.79$; $P < 0.01$) and legume × year ($F_{6,230} = 5.17$; $P < 0.01$) interactions (Table 2.2). No overall trend of leaf IVTD could be defined for tepary bean varieties in the legume × DAP interaction, except slightly higher values observed early in growing seasons (Figure 2.3C). While, guar varieties showed a higher leaf IVTD (870-920 g kg^{-1}) on 35 DAP and 90 DAP, lower concentrations were observed in the middle of the growing season. Although less pronounced, a similar trend in leaf IVTD was exhibited by soybean towards maturity. Within the year x legume interaction, the greatest amounts of leaf IVTD (857-876 g kg^{-1}) occurred in guar cv. Judd69 during both years, which was statistically similar to the other guar varieties in 2018 but differed during the 2017 (Figure 2.3D). In contrast, tepary bean and soybean possessed similar leaf IVTD, ranging between 814-839 g kg^{-1}, in both years.

The legume × DAP interactions ($P < 0.05$) were significant for both NDF ($F_{24,230} = 17.24$; $P < 0.01$) and ADF ($F_{24,230} = 4.73$; $P < 0.01$) concentrations in leaf biomass. Alternatively, the main effects of year and legume × year interactions ($P > 0.05$) were not significant (Table 2.2). Guar varieties maintained lower NDF and ADF concentrations in leaf biomass compared to other legumes throughout the growing season, though their fiber concentrations increase during the middle of growing seasons (Figure 2.3E, 2.3F). Similarly, soybean accumulated higher NDF (466 g kg^{-1}) and ADF (285 g kg^{-1}) concentrations in leaves at 50 DAP compared to other sampling dates. In contrast, the tepary bean varieties did not show any significant trend in either NDF and ADF concentrations in leaves with the advancement in plant maturity.

2.3.5. Stem nutritive values

Significant main effects of DAP ($F_{4,229} = 92.74$; $P < 0.01$) and year ($F_{1,229} = 132.45$; $P < 0.01$) were recorded for N concentrations in stems, while there were no significant legume effects or two-way interactions ($P > 0.05$; Table 2.2.). The N concentrations in stems of the legumes varied between 12.0 and 26.5 g kg^{-1} during growing seasons, with the highest N concentration observed on 35 DAP and the lowest on 90 DAP (Figure 2.4A). The decrease in stem N with DAP was explained ($P < 0.01$) by a cubic response. The average stem N concentration of legumes was found to be higher (19.9 g kg^{-1}) during 2018 than in 2017 (14.7 g kg^{-1}; Figure 2.4B).

Both legume × DAP ($F_{24,229} = 6.62$; $P < 0.01$) and legume × year ($F_{6,229} = 2.84$; $P < 0.05$) interactions were significant for stem IVTD concentrations. The greatest stem IVTD concentrations (833-875 g kg^{-1}) in the legume × DAP interaction was noted for guar varieties on 35 DAP, while tepary bean ranged between 700-740 g kg^{-1} and soybean had stem IVTD of 670 g kg^{-1} (Figure 2.5A). Soybean showed a constant decline in stem IVTD with DAP and resulted in the least digestible stems among the tested legumes throughout the growing season. In contrast, no such decline in stem IVTD was observed for guar or tepary bean, which was relatively constant from the middle to end of growing seasons. Tepary bean and guar varieties maintained similar stem IVTD, ranging between 666-716 g kg^{-1} in both years; a slightly lower value (634 g kg^{-1}) was recorded for tepary bean cv. White Sacaton in 2017 (Figure 2.4B). Soybean had the lowest stem IVTD among legumes in both years, averaging 529 and 581 g kg^{-1} in 2017 and 2018, respectively.

Significant legume × DAP and legume × year interactions were observed for both NDF and ADF concentrations in stem biomass of legumes (Table 2.2). The lowest concentrations of NDF and ADF in stems in legume × DAP interaction occurred in guar varieties on 35 DAP, while the highest concentrations of NDF (660-680 g kg^{-1}) and ADF (519-527 g kg^{-1}) were noted for soybean between 65 and 90 DAP (Figure 2.5C, 2.5E). Further, guar cv. Monument exhibited greater stem NDF (638 g kg^{-1}) and ADF (525 g kg^{-1}) than the other guar, or tepary bean, varieties on 90 DAP. Guar varieties showed an increase in fiber concentration until 50 DAP, and then maintained a relatively constant

NDF of 530-640 g kg^{-1} and ADF of 455-525 g kg^{-1} in their stem biomass during 65-90 DAP. In contrast, fiber concentrations in stems of tepary bean did not change substantially with increases in maturity, with stem ADF and NDF contents ranging between 520-610 g kg^{-1} and 390-490 g kg^{-1}, respectively.

Within the legume x year interactions, stems of guar cv. Judd69, guar cv. Matador and tepary bean cv. Brown Sacaton accumulated similar and consistent NDF concentrations, ranging between 522-563 g kg^{-1}, during both years (Figure 2.5D, 2.5F). The remaining four legumes accumulated greater NDF in their stems during 2017 than in 2018, with soybean accumulating the most NDF in both years. Tepary bean cv. White Sacaton and soybean contained greater stems ADF in 2017 than during 2018, while the other legumes produced similar ADF concentrations, ranging between 423-457 g kg^{-1}, in both years.

2.4. DISCUSSION

All tested legumes demonstrated some degree of adaptation to growing conditions of the SGP and could accumulate considerable amounts of biomass when used as a summer forage. Tepary bean cv. Black generated higher forage yields (4.4-5.3 Mg ha^{-1}) in both years and consistently outperformed soybean, the most-common summer legume in SGP (MacKown et al., 2007; Northup and Rao, 2015). Moreover, the study revealed the capability of tepary bean to accumulate biomass at a faster rate than soybean. Forage yields produced by tepary bean varieties were between 5.0-6.5 Mg ha^{-1} at 65 DAP (recommended time of harvest) in this study, which was comparatively higher than the average yields (4.4 Mg ha^{-1}) reported by Bhardwaj (2015) in Virginia. Double-cropping systems, involving winter wheat and summer crops in the Great Plains, often lead to yield losses in wheat due to over-extraction of soil moisture during summer (MacKown et al., 2007; Aiken et al., 2013). As such, fast-growing summer crops like tepary bean could be a more functional choice, better by providing adequate amounts of forage for grazing in shorter time periods, and also some fallow periods to recharge moisture within soil profile before winter wheat planting (Northup and Rao, 2015).

The forage yields of guar varieties (Matador and Monument) obtained during the late vegetative stage of growth (65 DAP) were similar to soybean, but were lower than amounts generated by Indian-origin cultivars (5855 kg ha^{-1}; Rao and Northup, 2013). These yield differences can be attributed to the late-maturity trait of Indian-origin cultivars, which allowed higher forage accumulation, compared to the cultivars included in the current study. The guar varieties also exhibited a degree of instability in yields across years, with higher yields in 2017 compared to 2018. A significant portion of this instability can be explained by the wet conditions and lack of competitiveness of guar with pigweed (*Amaranthus retroflexus* L.) that invaded guar plots during early in the 2018 growing season. Alternatively, the cultivars of tepary bean were not hampered (visual observations) by pigweed, due to its faster rate of growth and development of a dense ground cover early in the season. Soybean was also unaffected by pigweed in 2018, as the variety used was roundup (Glyphosate-based herbicide) ready which allowed a more efficient weed control. The amounts of forage produced by soybean was in agreement with the yield ranges observed by Rao and Northup (2009).

The leaf-to-stem ratio of forage species is an important factor affecting the intake of legumes by grazing animals (Annicchiarico, 2006). Generally, leaves are highly nutritious and stem possesses inferior nutritive value, which was also observed with tested legumes in this study. Consequently, legume forages with low leaf-to-stem ratios are not selectively grazed by cattle, which limits animal performance and gains when grazed (Rao and Northup, 2012). Though the nutritive value of leaves of guar was superior, and ADM was consistently high during 65-80 DAP, the leaf-to-stem ratios of guar biomass remained lower, and could limit its value as summer forage compared to other tested legumes. In contrast, tepary bean, especially Black, not only generated high forage yields, but also maintained higher leaf-to-stem ratios late in growing seasons (2.5-3.1 at 65 DAP).

The N concentrations in both leaf and stem biomass of the tested legumes declined with maturity, as was observed in other studies (Foster et al., 2009; Rao and Northup, 2009; Northup and Rao, 2015). These reductions in N content can be linked with declines in the concentration of photosynthetic enzymes with plant maturity (Gordon et al., 1982), and N remobilization during the grain-filling stage (Ortez et al., 2019). The average concentrations of N in leaves of the legumes (32-38 g kg^{-1}) were in accordance with the values reported by Rao et al. (2005) for forage soybean. The lower leaf N concentrations in tepary bean varieties could be explained by N dilution in their higher leaf biomass, as was observed in wheat (Lollato et al., 2019). While, the differences in N concentrations of both leaves and stems between two growing seasons could be due to the influence of biomass incorporation from the previous growing season, or differences in rainfall patterns (Raun et al., 2019).

Tepary bean has a vine-type growth habit, and retains older leaves while continuing to form new secondary/tertiary branches and leaves throughout the growing season. Therefore, the cell walls fractions (NDF and ADF) and IVTD stayed relatively uniform between 50-90 DAP. However, guar had a lower rate of leaf addition, and older leaves accumulated more NDF and ADF towards the middle of the growing season. Guar started senescing older leaves toward the end of growing seasons (80-90 DAP), and the remaining (fewer and younger) leaves resulted in a lower cell wall fractions and higher IVTD for leaf biomass. Similar changes in leaf composition could be assumed responsible for higher cell wall fractions in soybean leaves at 50 DAP. The annual variation in the components of cell walls and IVTD of legumes could be attributed to the environment, specifically differences in rainfall and subsequent biomass production (Buxton, 1996; Rao and Northup, 2009).

Plant maturity had a more significant impact on components of cell walls (NDF and ADF) and IVTD of soybean stems than the other legumes. Soybean plants developed thick fibrous stems with increasing maturity, so changes in cell wall fractions and IVTD of stems occurred at a higher rate. The NDF (610-660 g kg^{-1}) and IVTD (530-580 g kg^{-1}) concentrations of soybean stem were comparable to those reported by Foster et al. (2009). Although, the performance of soybean was similar to two of the varieties of tepary bean (White Sacaton and Brown Sacaton) in terms of biomass yields, leaf-to-stem ratio and leaf nutritive value, the presence of less digestible stems would lower its grazing value compared to tepary bean.

2.5. CONCLUSION

This research study compared the function of tepary bean and guar cultivars as potential summer forages under the growing conditions that exist in the SGP. Results showed that tepary bean cv. Black outperformed soybean and other legume cultivars by producing greater amounts of forage with higher leaf-to-stem ratios at the recommended date of harvest (65 DAP). While the other varieties of tepary bean did not exceed biomass yields and leaf nutritive value of soybean, their more-digestible stems indicate their superiority to soybean in overall nutritive value. The forage yields and nutritive value of leaves and stems of guar cultivars were comparable to other tested legumes, but a higher proportion of stems in biomass may limit their value as a forage. Therefore, tepary bean showed the greatest potential to generate high-quality summer forage for stockers in the SGP, in a more consistent fashion during a growing season. There is a need to define management practices to enhance the production of tepary bean, and to test its function in more extensive production settings for grazing or hay production. Research studies investigating systems-level water, fertilization, animal performance, and financial budgets of growing tepary bean in rotation with winter wheat are required for optimal and improved sustainability of forage-stocker production systems.

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Table 2.1. Monthly precipitation and temperature encountered during the summer growing seasons of 2017 and 2018, and long-term (2000-2019) averages (LTA).

	Precipitation (mm)			**Average temperature (°C)**		
Month	**2017**	**2018**	**LTA**	**2017**	**2018**	**LTA**
June	164	93	106	24.4	26.5	24.7
July	32	38	68	27.4	27.4	27.1
August	252	109	103	23.9	26.0	26.6
September	119	175	71	21.6	21.9	22.1

Table 2.2. Mixed model analyses of variance of aboveground dry matter (AMD), leaf-to-stem ratio, and nitrogen (N), neutral detergent fiber (NDF), acid detergent fiber (ADF) and in vitro true digestibility (IVTD) concentrations in leaf and stem of seven tested legumes.

Source	**AMD**	**Leaf-to-stem ratio**	**Leaf**				**Stem**			
			N	**NDF**	**ADF**	**IVTD**	**N**	**NDF**	**ADF**	**IVTD**
Rep	*	NS	**	NS	NS	NS	**	NS	NS	NS
Legume	**	**	*	**	**	*	NS	**	*	**
Year	NS	NS	**	NS	NS	**	**	**	**	**
Legume × Year	**	**	NS	NS	NS	**	NS	*	*	*
DAP	**	**	**	**	**	**	**	**	**	**
Legume × DAP	**	**	NS	**	**	**	NS	**	**	**

*$P<0.05$
**$P<0.01$
NS = non-significant at $P>0.05$

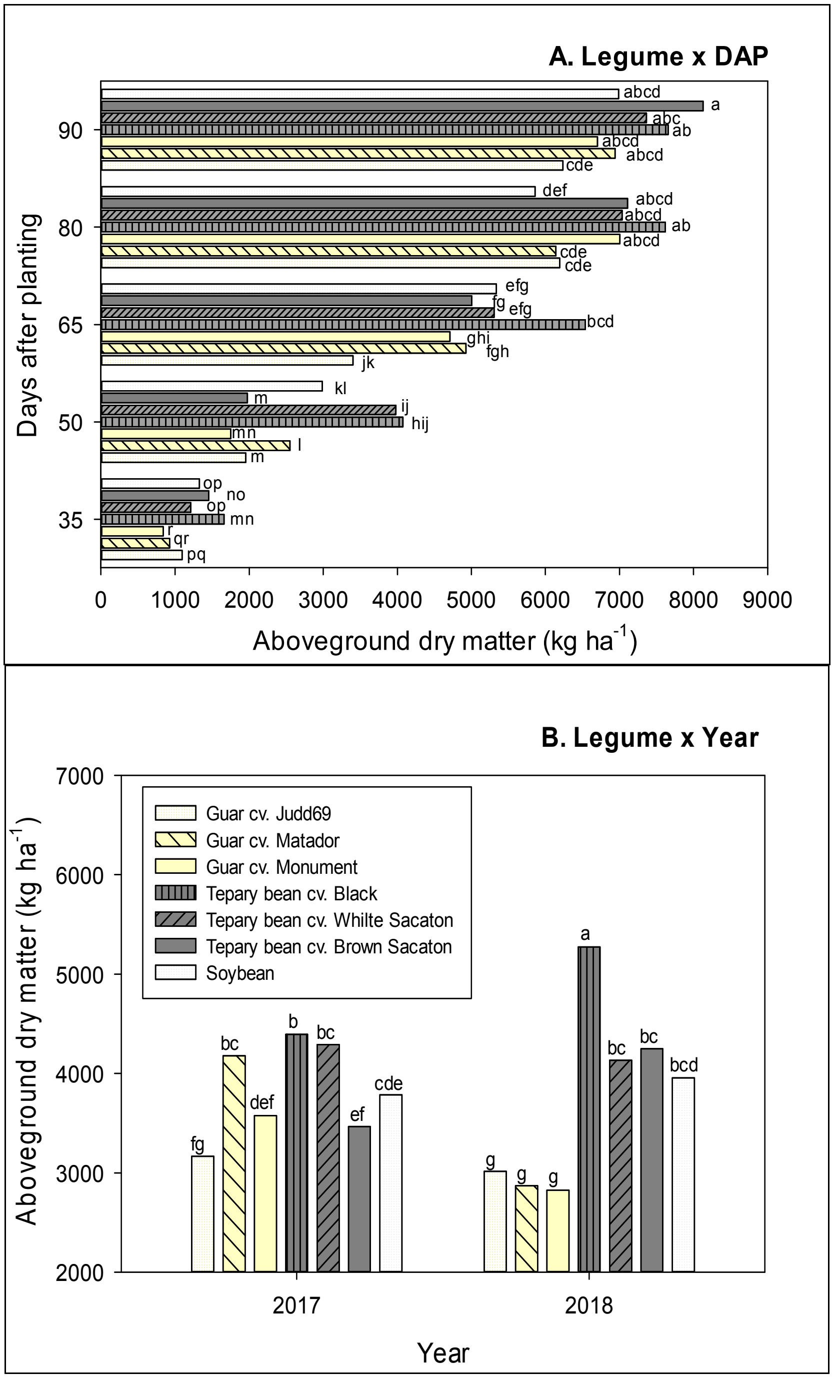

Figure 2.1. (A) Legume × days after planting (DAP) and (B) legume × year interactions of aboveground dry matter produced by seven warm-season legumes. Columns with the same letter within panels were not significantly different at *P* >0.05.

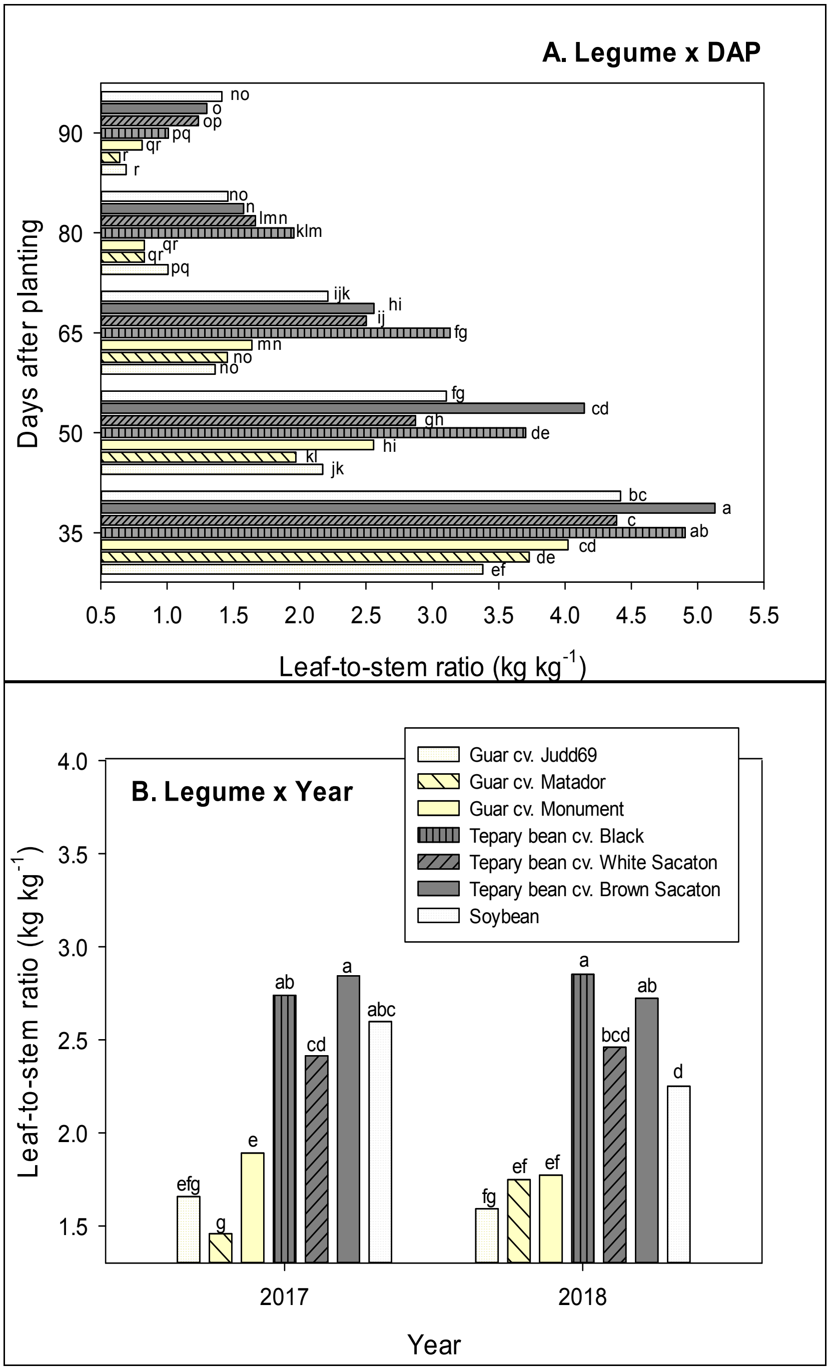

Figure 2.2. (A) Legume × days after planting (DAP) and (B) legume × year interactions of leaf-to-stem ratio in biomass of seven warm-season legumes. Columns with the same letter within panels were not significantly different at *P* >0.05.

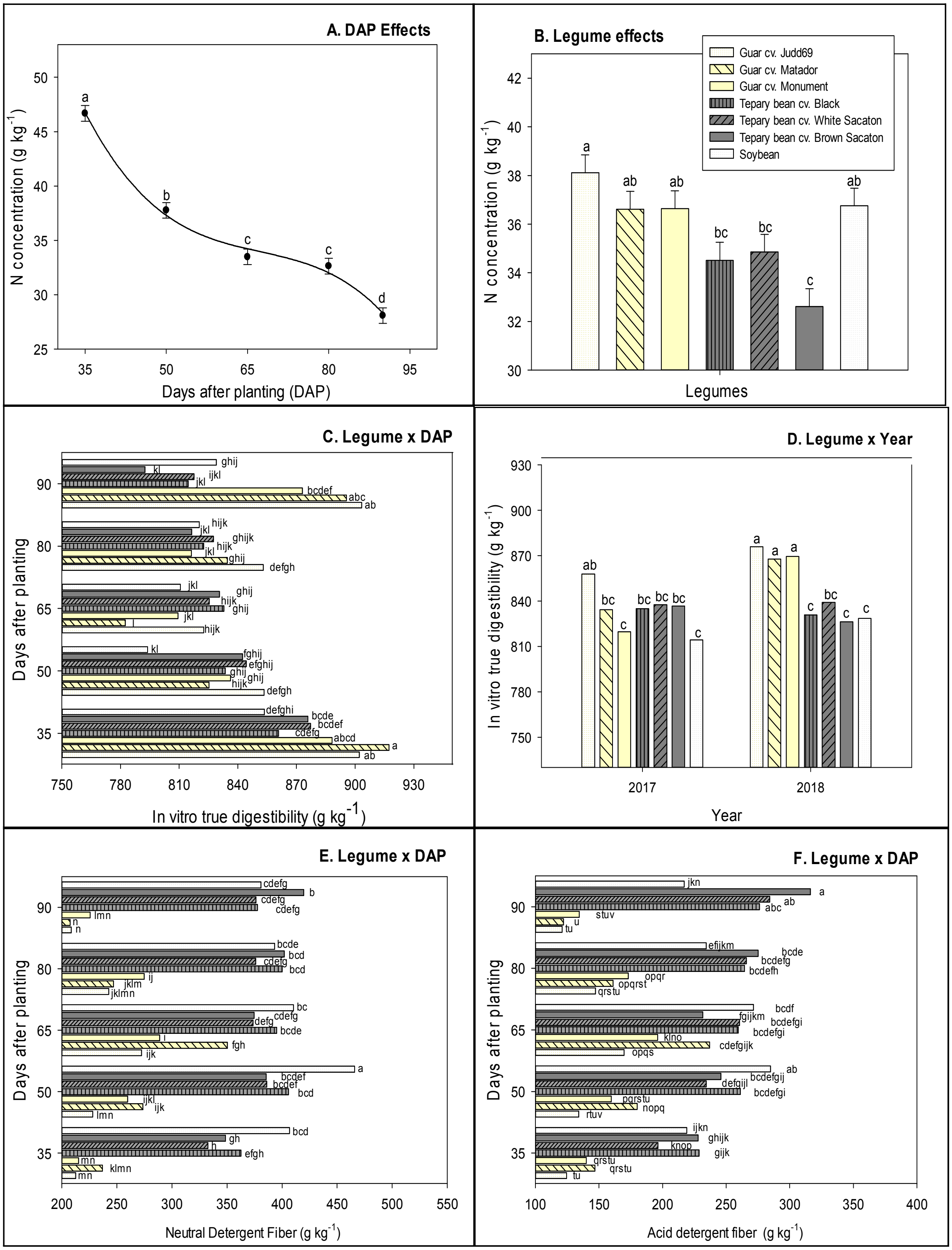

Figure 2.3. Main effects of (A) days after planting (DAP) and (B) legumes on N concentration, (C) legume × DAP and (D) legume × year interactions of in vitro true digestibility (IVTD), and legume × DAP interactions of (E) neutral detergent fiber (NDF) and (F) acid detergent fiber (ADF) concentrations in

leaves of seven warm-season legumes. Columns with the same letter within panels were not significantly different at *P* >0.05.

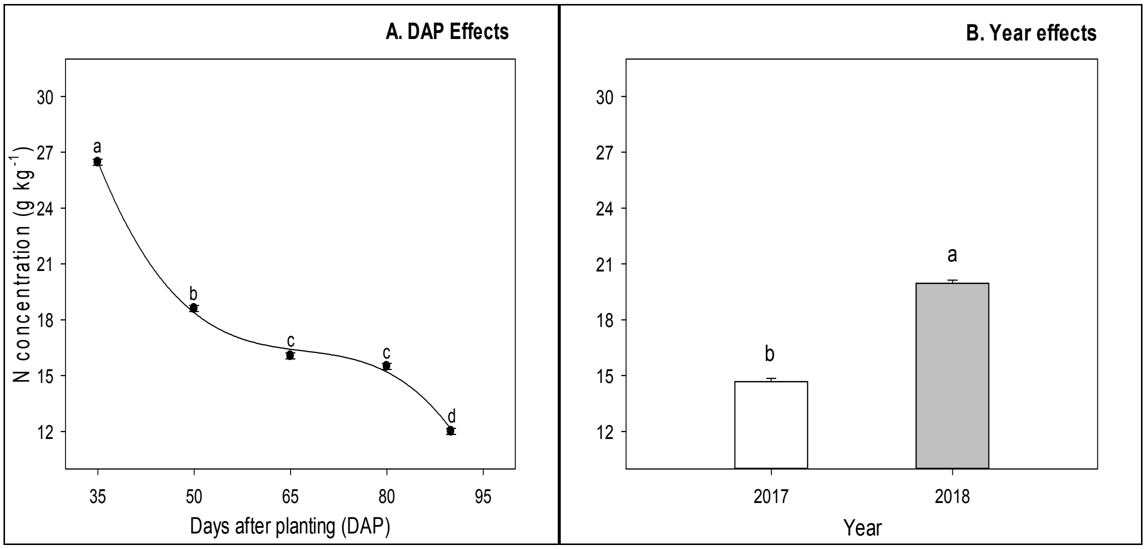

Figure 2.4. Main effects of (A) days after planting (DAP) and (B) year on N concentration in stem of seven warm-season legumes. Columns with the same letter within panels were not significantly different at *P* >0.05.

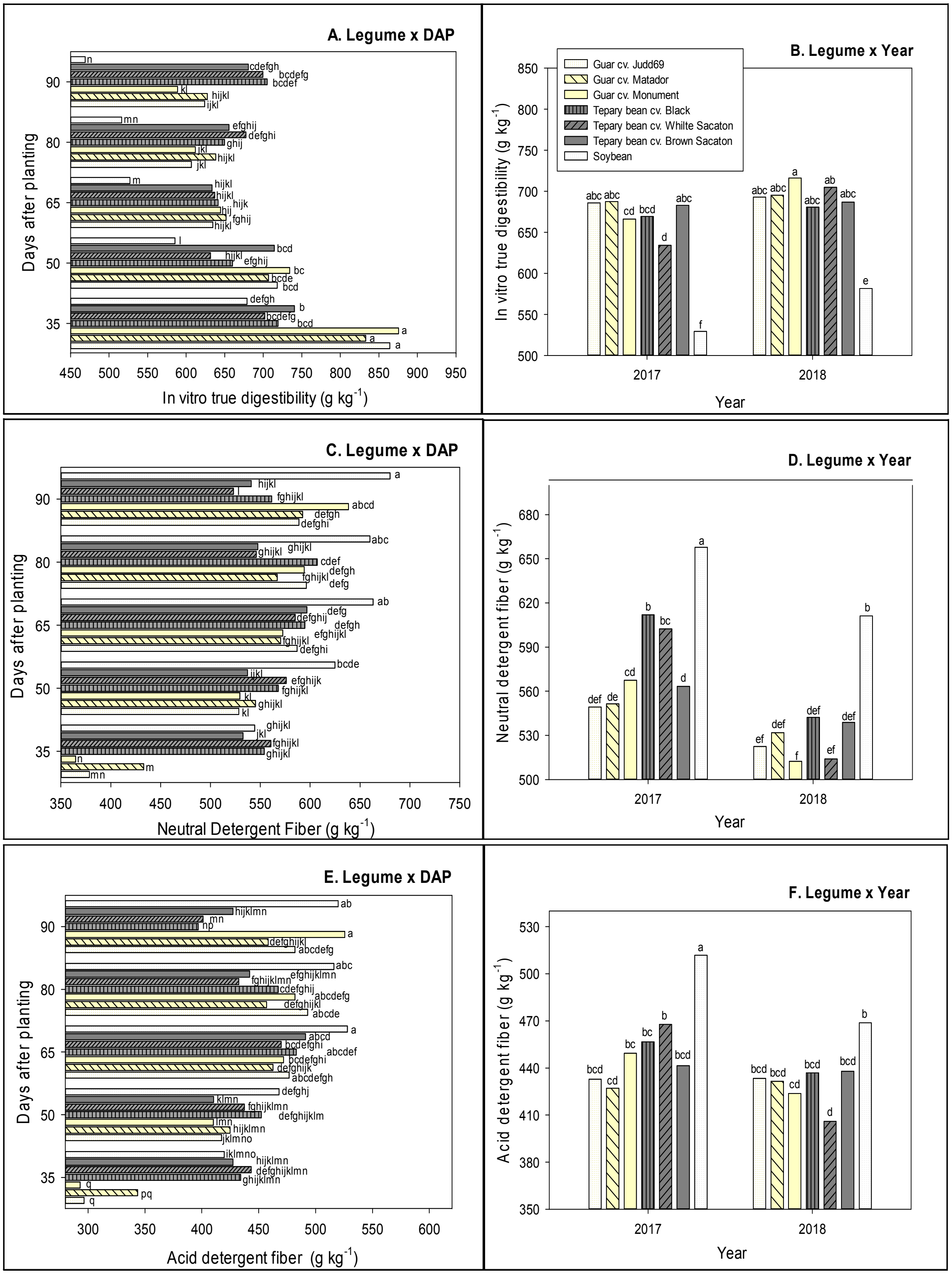

Figure 2.5. Legume × DAP interaction in (A) in vitro true digestibility (IVTD), (C) neutral detergent fiber (NDF) and (E) acid detergent fiber (ADF), and legume × year interaction in (B) IVTD, (D) NDF and (F) ADF in stem of warm-season legumes. Columns with the same letter within panels were not significantly different at *P* >0.05.

CHAPTER III

FORAGE YIELD AND QUALITY OF MOTHBEAN LINES UNDER THE SOUTHERN GREAT PLAINS CONDITIONS

This chapter has been published as "Baath, G.S., B.K. Northup, P.H. Gowda, K.E. Turner and A.C. Rocateli. 2018. Mothbean: A potential summer crop for the Southern Great Plains. American Journal of Plant Science. 9: 1391-1402."

ABSTRACT

Low nutritive value of available warm-season grasses during July through September limits the production of yearling stocker cattle in the southern Great Plains (SGP). There has been a continual exploration of species with the capacity to provide high quality forage during summer. Mothbean (*Vigna aconitifolia* [Jacq.] Marechal), a short-duration, drought tolerant crop is a promising choice for the SGP. This preliminary study evaluated the potential of mothbean as a summer crop for forage, grain or green manure. Results of this study with 10 mothbean lines from a range of geographic locations suggested that crop could be harvested 100 days after planting with dry biomass yield range of 7.3-18.1 Mg ha^{-1}. Mothbean forage contained 10.8-14.6% crude protein (CP), 32.0-41.7% neutral detergent fiber (NDF), 20.7-29.6% acid detergent fiber (ADF), and 73-84% in vitro true digestibility (IVTD) at maturity. Grain yield of the 10 mothbean lines varied from 91 to 1040 kg ha^{-1}. The 10 tested lines generated a high amount of nitrogen (N) rich biomass at maturity with total accumulated N of 163-316 kg ha^{-1} and a C: N ratio of 16:1 to 22:1.

Overall, performance indicators suggested that mothbean has considerable potential as an alternative crop for production of forage, grain, or green manure when grown as summer crop in rotation with winter wheat. Future research should focus on evaluating mothbean within different crop settings to define its capacity as green manure or summer forage to support production of stocker cattle in the SGP.

3.1. INTRODUCTION

The production of weight gains by yearling stocker cattle in the U.S. SGP depends on the availability of grazing pastures of winter wheat (*Triticum aestivum* L.) during fall and spring, perennial warm-season grasses such as bermudagrass (*Cynodon dactylon* (L.) Pers.) and old world bluestems (*Bothriochloa* spp.) during summer (Rao et al., 2002). However, the nutritive value of forage produced by these perennial grasses declines with maturity in early July, which can limit weight gain by stockers during summer without expensive protein supplements (Philips and Coleman, 1995). Based on the highly seasonal and variable growing conditions of the region (Schneider and Garbrecht, 2003), and the growth cycles of wheat and perennial warm-season grasses, there is no single crop with the potential to provide high quality forage year-round.

Alternate forage sources with the ability to fill the quality void that occurs during late-summer need to be explored to enhance the effectiveness of forage-stocker systems in the SGP. About 7,000 plant species are cultivated across the world, but only 20% have been used to satisfy 90% of food requirements for humans (Chivenge et al., 2015). The remaining species have been underutilized or neglected for different reasons. Bringing these under-utilized alternate crops from such a broad base into forage-stocker production systems as forages could enhance the sustainability of such systems, increase agro-ecosystem diversity, and address different components of the USDA-ARS Grand Challenge (USDA-ARS, 2017).

Past research has defined the potential use of some grain legumes as forage sources during summer (Rao et al., 2002; Rao and Northup, 2009, 2012, 2013; Northup and Rao, 2015, 2016). However, many of the tested legumes have significant amounts of large-diameter, low digestibility stems in their aboveground biomass which limits their applicability for grazing (Rao and Northup, 2012,2013). Thus, there is a need for additional exploration to define more effective novel legume species as summer forage. Selection of an appropriate species also requires consideration of the prevailing agro-climatic conditions of the SGP. The region frequently encounters prolonged droughts, and amount and occurrence of summer rainfall are highly erratic (Schneider and Garbrecht, 2003). Irrigation is not an option for most producers in the region, and those producers with irrigation are facing increasing limitations to the availability of ground water (Allen et al., 2007). Plant species capable of performing on variable and low amounts of soil moisture with minimal effects on subsequent wheat crops might fit well for summer crops. Furthermore, it would be advantageous to identify species with spreading-type growth forms that might also be used as cover crops or green manures, to reduce moisture loss, lower soil temperature, avoid soil erosion, and increase mineral N availability for the subsequent winter wheat.

Mothbean is an annual summer legume primarily grown as multi-purpose crop in the arid/desert regions of India due to its high heat and drought tolerance. It provides highly nutritious grains for human consumption, forage for cattle, and a green cover for soil. Mothbean grain is a good source of protein (23%), essential amino acids, carbohydrates, fiber, minerals, and vitamins which makes it a good source of nutrition for human diets (USDA-ARS, 2016). Growing mothbean could boost the supply of food and quality forage in arid and semi-arid regions across the world (National Academy of Sciences, 1979). The growth form of mothbean is prostrate, vining and semi-trail type which helps in conserving soil moisture, lowering soil temperature, and reducing soil erosion. As a legume, mothbean can also improve soil nutrition through nitrogen fixation.

Exploration of the potential forage use of mothbean was started in the U.S. in the early 20th century. A fresh mothbean forage yield of 4.4 Mg ha^{-1} was measured in northwest Texas, though without seed set (Conner, 1908). In the same period, yields of fresh weight of 60 and 45 Mg ha^{-1} under dryland and irrigated conditions, respectively, were measured near Fresno, California (Kennedy and Madson, 1925). They also reported a grain yield of 198 kg ha^{-1} from a study near Davis, California. Thereafter, the forage potential of this crop was neglected in the U.S. for unknown reasons, and no accounts on its forage productivity and nutritive value are available. Recently, grain yields ranging from 55 to 468 kg ha^{-1} for 54 lines of mothbean that were reported in the eastern U.S (Bhardwaj and Hamama, 2016).

The short growth cycle, food and forage potential, and soil conservation ability of mothbean suggest it may have the capacity to serve as a summer forage crop within the forage-stocker management systems used in the SGP. However, there is need to evaluate the capacity of genetic lines from different parts of the world for their adaptability and yields when grown under SGP’s agrometeorological conditions. The objectives of this study were to examine the adaptability of ten mothbean lines to growing conditions in the central region of the SGP, quantify their grain and forage yields, and define their potential nutritive value as forage and green manure.

3.2. MATERIALS AND METHODS

3.2.1 Experiment site and its Characteristics

This field study was conducted during the 2017 summer growing season (June through September) at the USDA-ARS Grazinglands Research Laboratory, near El Reno, OK (35˚ N, 98˚ W, elevation 414 m). Soil at the experiment site is described as Brewer silty clay loams (fine, mixed, superactive, thermic Pachic Udertic Argiustolls), with low permeability (0.2-1.5 cm h^{-1}), moderately well drained, 0-1 % slope, rarely flooded, and a pH of 6.9 (USDA-NRCS, 1999). Historical management of site involved growing wheat as a cover crop during the 10 years prior to the study by conventional tillage. The study site was conventionally tilled through a combination of disking (twice), rototilling (once), and culti-packing prior to planting. The amount of rainfall received during the growing season was 528 mm, with a variable pattern of distribution (Figure 3.1.). In contrast, the long-term (1994-2017) average precipitation for this period was 351 mm. Average daily maximum and minimum temperatures (Tmax and Tmin, respectively) during the growing season were 31˚C and 18˚C, respectively, which were approximate to the long-term averages.

3.2.2 Treatments and agronomic practices

Ten lines of mothbean (25 seeds/line) were obtained from the USDA-ARS Plant Genetic Resources Conservation Unit, Griffin, GA (Table 3.1.). Six lines (PI 271400, PI 271488, PI 288582, PI 288804, PI 288809, and PI 288810) are originally from India, two lines (PI 365427 and PI 426980) are from Pakistan, and PI 223521 and PI 372355 are originally from Afghanistan and Yemen, respectively. Most of the lines originated at more southerly latitudes than the study site. Experimental plots consisted of an individual row assigned to each line, spaced 60 cm apart. Seeds of each line were inoculated with cowpea-type *Rhizobium* spp. and hand planted 2 cm deep at 30 cm plant spacing on 30 May. Dry granular 18-46-0 fertilizer was applied at the rate of 100 kg ha^{-1} prior to planting to provide P. Weed control was achieved by one hand weeding at 30 days after planting.

3.2.3 Data Collection and Statistical Analysis

Three locations along rows assigned to each line were randomly chosen for sampling at end of growing season (13 Sep 2017). Measurements of canopy height were taken from the soil surface to top of the canopy for each plot prior to harvesting. Samples of aboveground biomass were collected on the same day by clipping 0.5-m row lengths from each plot and fresh weights of samples were determined. All plant biomass related to plants within sampled row lengths were identified and included in samples. All samples were dried in a forced-air oven (60˚C) to a constant weight and dry biomass was calculated. Pods were separated and threshed to obtain grain yield stored for use in future experiments. The forage component (leaf and stem) of each sample was ground to pass a 2-mm screen in a Wiley mill, and stored at room temperature for laboratory analyses. Total nitrogen (N) and carbon (C) concentrations were determined by flash combustion and analyzing gases evolved from samples in an auto-analyzer (Model VarioMacro, Elementar Americas, Inc., Mt. Laurel, NJ).

Total amounts of accumulated N in aboveground biomass (kg N ha^{-1}) were calculated from amount of biomass collected and N concentrations in biomass. Crude protein (CP) was calculated by multiplying total N concentrations by 6.25. Percentage of neutral and acid detergent fibers (NDF and ADF, respectively) in biomass samples were determined by techniques outlined by Goering and Van Soest (1970) and Van Soest et al. (1991) using a batch processor. In vitro true digestibility (IVTD) was determined using techniques for a Daisy Digester (Ankom Technology Corp., Fairport, NY).

Measurements and biomass samples were collected randomly (independently) within each row (line of mothbean) and considered as pseudo-replicates (Gomez, 1984). Data were analyzed using one-way analyses of variance (ANOVA) to identify the differences among the 10 lines for yields, CP, NDF, ADF, IVTD and accumulated N using proc GLM in SAS version 9.4 (SAS Institute, 2013). Differences among mean responses were defined by Least Significance Difference (LSD) post hoc test at 5% significance level (Steel and Torrie, 1980).

3.3. RESULTS AND DISCUSSION

3.3.1. Adaptability

Excellent emergence (> 90%) was visually observed with all 10 lines after 124 mm rain had accumulated three days after planting. Since these seeds were 40-60 years old, successful emergence revealed the potential of mothbean seeds held in long-term storage to sustain germination without any seed treatments. However, after the rainfall events occurred during the first week post-planting, a prolonged dry period occurred in June-July, with only 30 mm rain received, followed by over 250 mm in August (Figure

1). Most of the lines of mothbean showed slow growth throughout the dry period, but stayed green. Only PI 288809 failed to survive due to unknown reasons. All lines of mothbean reached physiological maturity within 90-100 days after planting except PI 372355, which did not flower probably due to its source from much southerly latitude (Table 3.1.).

3.3.2. Canopy height

Canopy height, dry biomass, and grain yields of mothbean lines differed ($p < 0.05$). The final canopy height of mothbean lines was found to be within a range of 20-32 cm (Table 3.2.). The PI 223521 line showed maximum canopy height among the nine surviving lines due to its different growth habit, which is semi-prostrate. This growth form was observed visually in the field and also reported by Germplasm Resources Information Network (GRIN) database (Table 3.1.). The lowest canopy height was recorded for PI 288804 among the nine lines, which was not different ($p > 0.05$) from that of PI 288582 and PI 372355. The canopy heights of PI 271488, PI 288804, and PI 288810 were found to be lower than the values reported in the GRIN database (Table 3.1.).

3.3.3. Grain yield

Grain yield varied among mothbean lines from 91 to 1040 kg ha^{-1} (Table 3.2.), which was overall higher than the yield range reported in the eastern U.S. (Bhardwaj and Hamama, 2016). The PI 271488 and PI 426980 lines showed higher grain production, which was in agreement with the GRIN database (Table 3.1.), while lower grain production was observed for PI 365427, PI 271400, and PI 288804. Grain production of all other lines matched the yields stated by GRIN, except PI 288804, PI 288810, and PI 365427, which were found to be lower (Table 3.2.). In regions like the SGP, grain production is not likely to be as important as forage production. However, if mothbean can be used as forage resource in the SGP, producers will need a source of seed for planting. Sufficient seed production would make use of mothbean in the region feasible and results in improved efficiency on farming operations. Viable grain yields could also allow SGP producers the opportunity to meet a growing demand for mothbean as a food grain in the future as the human population continues to grow.

3.3.4. Forage yield

There were no reports on forage yield for any of the chosen mothbean lines in the GRIN database. In this study, yield of dry biomass of mothbean lines was found to be 7.3-18.1 Mg ha^{-1} (Table 3.2.). The PI 288810 line produced the greatest amount of biomass among the nine lines, though the yields of PI 271488 and PI 288582 were similar. These results were in agreement with the forage yield of mothbean lines reported during the early 20th century by Kennedy and Madson (1925). In comparison, the lowest yields during our study were observed for PI 223521, with low yields by PI 271400, PI 288804, PI 365427, and PI 426980 that were similar (Table 3.2.). The amount of dry biomass produced by all lines were above levels (1.1 Mg ha^{-1}) required to avoid any limitations on forage availability that could affect intake by yearling cattle on pasture (Coleman et al., 2010).

3.3.5. Nutritive value of forage and its comparison to other forages

Differences were noted for CP and NDF concentrations among the mothbean lines (Table 3.3.). In contrast, concentrations of ADF and IVTD among lines were similar. The CP content of mothbean lines at maturity ranged between 10.8-14.6%. Among lines, higher CP was observed in PI 271488 followed by PI 372355, PI 223521, PI 271400, and PI 288804; however, these lines were not different from each other ($p < 0.05$; Table 3.3.). Furthermore, the average CP values of the top six lines varied only 1.62% from the highest (14.63%) to the lowest (13.01%). The CP concentration was numerically lower in PI 288582, followed by PI 365427, and PI 426980 and these lines were not significantly different from each other. The NDF concentration at maturity of tested lines ranged from 32.0-41.7% (Table 3.3.). The PI 271488 line had numerically the lowest NDF concentration, but was only significantly different from PI 271400, PI 365427, PI 372355, and PI 426980. There was no difference in ADF among the mothbean lines despite a range of 20.7-29.6% (Table 3.3.). The IVTD of all mothbeans was not different ($p < 0.05$) from each other and ranged between 73-84% at maturity. Generally, measures of nutritive value of forage were reported to decline with increasing maturity in most of the forage legumes tested in the SGP (Rao and Northup, 2009, 2012, 2013). However, the nutritive value of tested mothbean lines at maturity was still above requirements (10.5% CP and 67.5% IVTD) of cattle weighing 300 kg and gaining 1 kg d^{-1} (Coleman et al., 2010).

Based on our results (Table 3.2. & 3.3.), PI 271488 appeared to be an interesting candidate for the SGP region. The PI 271488 line not only showed high grain yield production, but also equal or superior forage yield and nutritive value compared to the other lines. A generalized comparison of nutritive value of mothbean i.e. PI 271488 forage with that of soybean (*Glycine max*; Rao and Northup, 2009), guar (*Cyamopsis tetragonoloba*; Rao and Northup, 2013), and pigeon pea (*Cajanus cajan*; Rao and Northup, 2012) at maturity is presented in Table 3.4., though weather and soil conditions were different across the studies. In the past research conducted in the SGP, both guar and pigeon pea produced high forage yields on limited moisture but their low digestibility stems appeared to be a limitation to grazing (Rao and Northup, 2009, 2012, 2013). In this study, plant biomass of mothbean appeared to be superior to guar and pigeon pea in both CP and IVTD.

Soybean has been used as a control for forage quality comparisons in many studies testing annual legumes as summer forage. Under weather and soil conditions similar to this study, some annual legumes outperformed soybean in some, but not all aspects of forage quality except lablab (*Lablab purpureus* (L.) Sweet; Northup and Rao, 2015). However, amount of biomass production by both soybean and lablab was limited by low precipitation. In contrast, mothbean lines evaluated in this study persisted through a continuous 8-week drought in the current study and still produced good amounts of biomass. Therefore, mothbean could be a better fit in limited moisture conditions of the SGP. Although, it was comparatively lower in CP than soybean, the IVTD of mothbean forage was higher (Table 3.4.). Mothbean pods were separated from the forage samples in this study, and have approximately 18-19% CP (G. Baath, unpublished data). Therefore, whole plant biomass of mothbean (including pods) in a pasture setting would have CP concentrations that were competitive to soybean. However, the function of mothbean in a grazed setting needs to be evaluated to define its capacity to support stocker growth in the region.

3.3.6. Green Manure potential

In this study, the lines of tested mothbean had a vigorous trailing and viney growth habit, which completely covered the soil with long trailing stems and leaves, and functioned to help control weed growth. Amounts of total N accumulated in aboveground biomass were different among mothbean lines and ranged from 163-316 kg ha^{-1} (Table 3.5.). The PI 288810, PI 271488, and PI 288582 lines accumulated comparatively high amounts of N due to greater amounts of accumulated biomass. The C: N ratio of mothbean lines ranged from 16:1 to 22:1 with the PI 288582, PI 288804, PI 365427, and PI 426980 lines having higher ratios than the remaining lines (Table 3.5.).

Earlier research on green manure applications in the SGP found that soybean and lablab accumulated 65 to 80 kg N ha^{-1} by the end of growing season but were not effective at enriching soil N (Northup and Rao, 2015). Similar results were reported in a study testing soybean (accumulated 48 kg N ha^{-1}) as green manures in rotations of winter wheat grown for pasture and hay production in central Oklahoma (MacKown et al., 2007). The amounts of N accumulated and C: N ratios observed in this study indicate mothbean has potential to serve as a green manure, and provide large amounts of mineral N for subsequent crops of winter wheat. Further research on quantifying the agronomic benefits from mothbean-winter wheat rotation in the SGP can bring more insight on its green manure aspect.

3.4. CONCLUSION

Mothbean lines from different geographic locations (more southerly latitudes compared to Oklahoma) showed a range of adaptability to the agro-climatic conditions of the SGP. All mothbean lines, except PI 288809, tolerated the hot and dry conditions that occurred during June-July and generated 7.3-18.1 Mg ha^{-1} dry biomass in response to precipitation received during the later parts of the growing season. Tested lines of mothbean were also capable of producing grain at the more northerly latitude of the study site, though there was a wide range in production (91 to 1040 kg ha^{-1}). The higher forage and grain yields noted within the ranges of responses indicated some potential for genetic improvement that can provide lines more capable of generating both grain and forage.

This study has also provided a base-line for the nutritive value of forage produced by mothbean that was not available within the existing literature. Mothbean possessed medium amounts of CP, low NDF and ADF concentrations and high IVTD at maturity, which highlights the capacity to support grazing by stocker cattle during summer in the SGP. The study also revealed the high green manure potential of mothbean as it generated large amount of N rich biomass that completely covered the soil. Future research should focus on evaluating mothbean within different crop settings to define its capacity as green manure or summer forage to support production of stocker cattle or as stored feed in the SGP.

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Table 3.1. Characteristics of ten mothbean lines from the USDA-ARS Plant Genetic Resources Conservation Unit grown at El Reno, OK, as described by the Germplasm Resources Information Network (GRIN).

GRIN ID	**Source**		**Plant Maturity**	**Growth Habit**	**Plant Height**	**Grain Yield**	**Received**
	Location	**Latitude**					
		˚N	(days)		(cm)		(Year)**
PI223521	Afghanistan	34.7	90	Semi-prostrate	NA*	Medium	1955
PI271400	India	20.0	110	Prostrate	20	Limited	1961
PI271488	India	26.4	130	Prostrate	43	High	1961
PI288582	India	28.3	85	Prostrate	25	Medium	1963
PI288804	India	23.0	130	Prostrate	35	High	1963
PI288809	India	31.7	90	Prostrate	25	Low	1963
PI288810	India	23.4	130	Prostrate	40	High	1963
PI365427	Pakistan	34.8	90	Prostrate	23	Medium	1971
PI372355	Yemen	14.1	90	Prostrate	NA*	Limited	1972
PI426980	Pakistan	32.6	75	Prostrate	20	High	1978

https://npgsweb.ars-grin.gov/gringlobal/accessiondetail.aspx?id=1218458 (accessed 15 February 2018)

*NA = Not Available

**Year in which the GRIN received seed

Table 3.2. Canopy height, dry biomass, and grain yield of ten lines of mature mothbean at El Reno, OK.

GRIN ID	**Location**	**Canopy Height**	**Grain Yield**	**Dry Biomass**
		(cm)	(kg ha^{-1})	(Mg ha^{-1})
PI223521	Afghanistan	31.7 a	427.2 cd	7.30 c
PI271400	India	24.1 bc	98.5 e	8.67 bc
PI271488	India	24.5 bc	1040.5 a	13.49 ab
PI288582	India	21.6 cd	652.7 bc	18.00 a
PI288804	India	20.3 d	189.4 de	11.14 bc
PI288809	India	-	-	-
PI288810	India	24.1 bc	551.6 bc	18.11 a
PI365427	Pakistan	25.8 b	91.6 e	11.79 bc
PI372355	Yemen	21.5 cd	-	11.20 bc
PI426980	Pakistan	25.4 b	848.4 ab	8.99 bc
Mean		24.4	433.3	12.07
p-value		<0.0001	<0.0001	0.0051
LSD		2.96	319.06	5.55

Values within each column followed by same letter(s) are not different according to least significance difference (LSD) test ($p \leq 0.05$).

Table 3.3. Forage nutritive value of whole plant biomass of 10 lines of mothbean at maturity.

GRIN ID	Location	CP	NDF	ADF	IVTD
		----------------- (%; dry matter basis) ----------------			
PI223521	Afghanistan	13.85 ab	36.22 bcd	25.62	77.31
PI271400	India	13.41 abc	38.20 abc	25.05	83.38
PI271488	India	14.63 a	32.03 d	20.73	78.95
PI288582	India	10.83 d	36.18 bcd	23.54	80.85
PI288804	India	13.09 abc	35.93 bcd	24.13	81.06
PI288810	India	13.01 abcd	34.91 cd	22.21	81.36
PI365427	India	11.31 cd	40.47 ab	28.01	78.29
PI372355	Pakistan	14.49 a	41.67 a	29.59	73.06
PI426980	Yemen	12.23 bcd	38.13 abc	26.42	83.10
Mean		12.98	37.08	25.03	79.71
p-value		0.022	0.034	NS	NS
LSD		2.23	5.19	-	-

Values within each column followed by same letter(s) are not different according to least significance difference (LSD) test ($p \leq 0.05$). NS = Non-significant at $p > 0.05$.

Table 3.4. Comparisons of forage quality of mothbean, soybean, guar, and pigeon pea at maturity.

Forage traits	**Mothbean**	**Soybean**	**Guar**	**Pigeon pea**
CP%	14.6 (0.3)	17.5 (0.6)	9.6 (0.2)	13.9 (0.5)
IVTD%	78.9 (3.3)	75.0 (1.2)	52.5 (1.5)	57.2 (0.6)
References		Rao and Northup, 2009	Rao and Northup, 2013	Rao and Northup, 2012

*Values in the parentheses represent standard errors of means.

Table 3.5. Amount of accumulated N in aboveground biomass by mothbean lines and their C: N ratio at maturity.

GRIN ID	**Source location**	**Accumulated N**	**C:N**
		(Kg ha^{-1})	
PI223521	Afghanistan	163.3 c	16.81 c
PI271400	India	184.0 c	18.11 bc
PI271488	India	316.4 ab	16.13 c
PI288582	India	310.2 ab	21.92 a
PI288804	India	229.0 bc	18.57 abc
PI288810	India	376.8 a	18.23 bc
PI365427	India	219.1 bc	21.52 ab
PI372355	Pakistan	259.0 bc	16.71 c
PI426980	Yemen	174.4 c	19.56 abc
Mean		248.0	18.62
p-value		0.0134	0.0225
LSD		117.1	3.47

Values within each column followed by same letter(s) are not different according to least significance difference (LSD) test ($p \leq 0.05$).

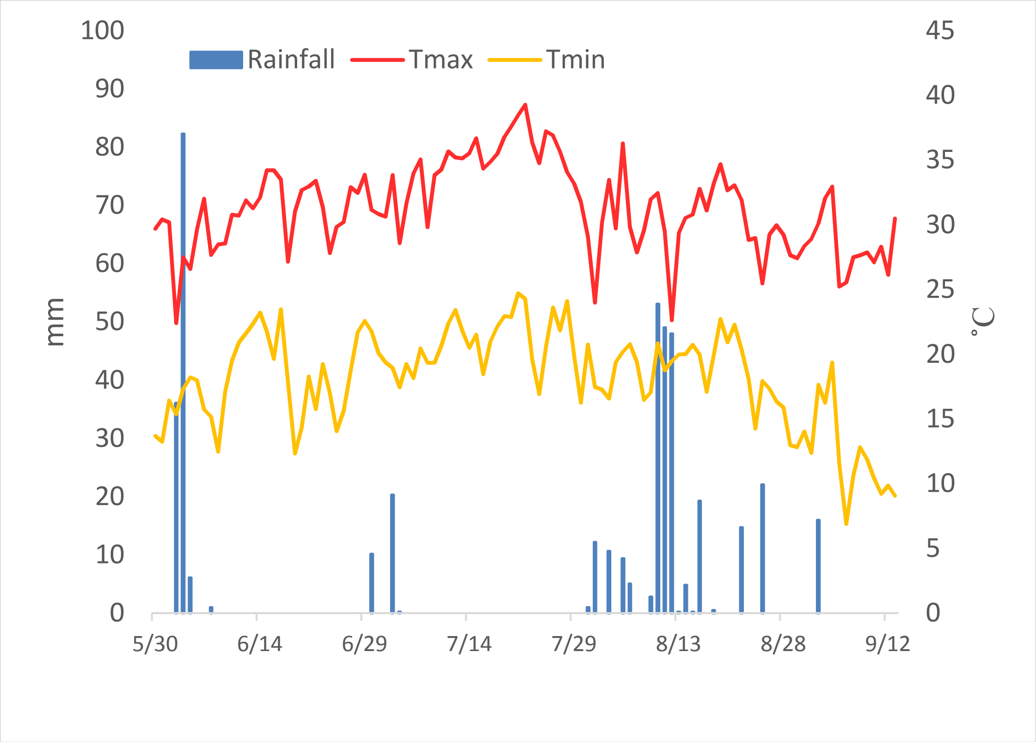

Figure 3.1. Rainfall and temperature encountered during the summer growing season of 2017 at El Reno, OK. Tmax and Tmin signify the daily maximum and daily minimum temperatures, respectively.

CHAPTER IV

ADAPTABILITY AND FORAGE CHARACTERIZATION OF FINGER MILLET ACCESSIONS IN U.S. SOUTHERN GREAT PLAINS

This chapter has been published as “Baath, G.S., B.K. Northup, P.H. Gowda, A.C. Rocateli and K.E. Turner. 2018a. Adaptability and forage characterization of finger millet accessions in US Southern Great Plains. Agronomy. 8:177.”

ABSTRACT

Low forage quality of available perennial warm-season grasses during mid through late summer affects production of stocker cattle in the U.S. Southern Great Plains (SGP). Finger millet (*Eleusine coracana* Gaertn L.), a drought tolerant annual grass, could be a promising forage for the SGP. This field study assessed the adaptability and forage characteristics of 11 finger millet accessions originally sourced (1964 -1981) from different parts of the world. Results of this study suggested that finger millet can generate forage yields ranging from 5.0-12.3 Mg ha^{-1} at 165 days after planting. Finger millet forage contained 105-156 g kg^{-1} crude protein, 598-734 g kg^{-1} neutral detergent fiber, 268-382 g kg^{-1} acid detergent fiber, 597-730 g kg^{-1} in vitro true digestibility, and 387-552 g kg^{-1} neutral detergent fiber digestibility. Ten of the 11 accessions flowered and produced grains with yields varying from 60-1636 kg ha^{-1}. Overall, finger millet has the potential to serve as an alternative crop for production of forage, and possibly grain,

in the SGP. Further research needs to be focused on developing strategies for agronomic management and evaluating the capacity of finger millet under different grazing and hay production settings in the SGP.

4.1. INTRODUCTION

Winter wheat (*Triticum aestivum* L.) based production systems are the primary choices of producers in the U.S. Southern Great Plains (SGP). An average of 2.06 million ha was planted annually in Oklahoma during 2013 through 2017 (USDA-NASS, 2017). Most of the winter wheat is conventionally tilled and grown in continuous rotations, separated by periods of summer fallow, under rainfed conditions. Winter wheat is grown to produce grain, forage, or forage-grain combinations of products (Decker et al., 2009; Edwards et al., 2011). Summer fallow during June to September is considered as a conservative technique that helps to store moisture for the following wheat crop. However, the winter wheat-summer fallow system has various concerns pertaining to sustainability, such as the presence of low amounts of forage before and after available wheat paddocks (Northup and Rao, 2015), low efficiency in usage of precipitation and available soil water by wheat-summer fallow systems (Patrignani et al., 2014), increased vulnerability to soil erosion through conventional tillage, and reduced amounts of organic nitrogen and carbon in soils (Kelley and Sweeney, 2010).

Grazing low-cost pastures of forages to generate gain by yearling stocker cattle is an important component of agriculture in the SGP (Phillips and Coleman, 1995; Fieser et al., 2006), and a key strategic feature of the beef production system of the U.S. (Baath et al., 2018). Stocker cattle in the region rely on wheat pasture from winter through spring, and pastures of introduced perennial warm-season grasses such as old world bluestems (*Bothriochloa* spp.) and bermudagrass [*Cynodon dactylon* (L.) Pers.] for late spring and summer grazing (Phillips and Coleman, 1995). However, high quality forage becomes unavailable during July through late September as the amount of high quality biomass provided by these perennial grasses declines. There has been a continual search for alternative crops with the capacity to act as cover and produce quality forage during late-summer. Past research has focused on defining the potential of grain legumes (pulses) as forage (Baath et al., 2018). Many of the studies reported the aboveground biomass of most pulses possessed large proportions of low digestible stems which could be a limitation in grazing applications (Rao and Northup, 2009, 2012, 2013). Therefore, further exploration of other species of grasses and legumes that may function as summer crops needs investigation, to enhance the sustainability of forage-stocker production systems of the SGP.

Finger millet (*Eleusine coracana* Gaertn L.) is an annual grass, native to the Ethiopian and African highlands and widely adapted to a range of different growing conditions. Finger millet is an important cereal crop in many drought-prone regions across the world (Upadhyaya et al., 2010). Its primary growing area ranges from 20˚N to 20˚S in the semiarid to arid tropics, though finger millet is grown in areas to 30˚N (Himalayan regions of India and Nepal). A minimum temperature of 8-10˚C is needed for germination and warm conditions involving an average temperature of 26-29˚C leads to its optimum growth (Gangaiah and Gautam, 2008). Finger millet yields about 1-1.5 Mg ha^{-1} grain and 3-9 Mg ha^{-1} fodder under dryland conditions in India. It also has a high water use efficiency and consumes 10-20% lesser water than sorghum [*Sorghum bicolor*

(L.) Moench] under irrigated conditions (Kissan, 2016). Finger millet can tolerate some degree of waterlogging or salinity, but it is sensitive to frost (Satish et al., 2016).

Finger millet has served as a safeguard against malnutrition during drought and is a staple food in some regions of India, and eastern and central Africa (Singh and Raghuvanshi, 2012). It is utilized in many ways including as bread, porridge, malt, popped products and in both alcoholic and non-alcoholic brewing industries (Shobana et al., 2013). The seed of finger millet contains 7-14% protein, 73% carbohydrate, 1.5% fat, and 3.6% fiber. The seed is also higher in Ca, P, Fe, and Mn than other cereal grains and is considered an ideal food for breastfeeding mothers, growing children, and the infirmed (National Research Council, 1996). It was found out to be useful in controlling blood glucose levels and recommended for diabetic patients (Kumari and Sumathi, 2002). Moreover, finger millet seed does not possess gluten and is considered ideal for celiac patients (Devi et al., 2014).

Forage produced by finger millet is highly nutritious and fed to livestock in several African and Asian countries. Nutrient concentrations of crude protein (CP; 10.7%), Ca (1.20%), P (0.44%), K (4.53%), and Mg (0.31%) levels were reported in biomass of 4 finger millet accessions grown in the semi-arid Texas High Plains that were higher than forage corn (*Zea mays* L.) and forage sorghum (Gowda et al, 2015).

Despite its several beneficial traits, lack of scientific research evaluating finger millet potential as a grain or forage crop limits its adoption worldwide. Most of the available research findings are derived from India which primarily aimed at the nutritional properties of finger millet grain compared to other crops. In the U.S., promising forage quality results were observed when testing five accessions of finger millet under irrigated conditions in the Southern High Plains (Gowda et al., 2015). However, other researchers observed restricted grain production due to finger millet photoperiod sensitivity in central California and the Texas Panhandle (National Research Council, 1996). This issue might be true to the SGP, which make photo-insensitive varieties the best alternative to the region. Consequently, there is a fundamental need to evaluate photo-insensitive varieties to determine their climate adaptability, drought tolerance, yield capabilities, and nutritive value in order to assess the potential of finger millets as summer forage for the SGP. The specific objectives of this study were to: 1) assess the adaptability of 11 finger millet accessions to summer conditions of the SGP and 2) define their capabilities as a summer forage crop.

4.2. MATERIALS AND METHODS

This study was carried out at the USDA-ARS Grazinglands Research Laboratory (35° N, 98° W, elevation 414 m), near El Reno, OK in 2017. For this study, 11 accessions of finger millet (250 seeds/accession) were collected from the USDA-ARS Plant Genetic Resources Conservation Unit, Griffin, GA (Table 4.1.). These accessions were sown on 20 April into germinating trays (56 × 28 × 6 cm) with a Canadian sphagnum peat moss based mixture and kept in a greenhouse at 25/20°C (day/night) with regular irrigation for five weeks. The purpose of maintaining plants in the greenhouse was to ensure maximum germination and establishment, given the limited number of seeds available per accession.

Seedlings were hand transplanted on 25 May into a field plot, which was disked twice, rototilled, and culti-packed prior to transplanting. The soils on the experiment field were characterized as Brewer silty clay loams (fine, mixed, superactive, thermic Udertic

Argiustolls) with a pH of 6.9, 0-1% slope, low water permeability (0.2-1.5 cm h^{-1}), moderately well drained, and rarely flooded (USDA-NRCS, 1999). Prior to this study, the site was managed through conventional tillage and used for growing wheat as a cover crop during the previous 10 yrs.

Each accession was assigned to three replicate experimental plots, which consisted of single 15-m length rows spaced 60 cm apart, with ~30 cm spacing between individual plants. About 50 mm total water was applied in three irrigations on alternate days with a sprinkler system to ensure good establishment of seedlings after transplanting (Figure 4.1.). Urea (46-0-0) was applied at the rate of 100 kg ha^{-1} to ensure no N limitations for the crop at 30 d after transplanting. Broadleaf weeds were controlled by application of 2,4-Dichlorophenoxyacetic acid herbicide, and grass weeds were hand weeded at 30 d after transplanting.

The agronomic management of finger millet in this study is similar to techniques used to grow finger millet for grain in India and Africa. In these regions, seeds are broadcast into nursery beds, and watered for 21 to 30-days to ensure seedling growth. Thereafter, seedlings are transplanted into 0.6 to 1.0 m spaced rows, in widely spaced (up to 30 cm) clumps (3 to 6 plant per clump) within rows, and irrigated after transplanting and as needed during growing seasons. Our use of a similar approach (wide rows and widely spaced plants) allowed some comparison of responses of accessions to results from earlier studies (Gowda et al., 2015). This approach also allowed for optimum use of the limited amounts of seed available (n=250 per accession); to define the capacity of tested accessions to produce both forage and grain in the SGP.

Harvesting of accessions was done at 130 days after transplanting, prior to occurrence of the first potential freeze for the experimental site (USDA-NRCS, 1999). Before harvesting, canopy height was measured from the soil surface to top of spikelet for each accession. Samples of aboveground biomass were collected by clipping 0.5-m row lengths from each plot. All whole biomass samples were dried to a constant weight in a forced-air oven at 60°C and their dry weights recorded. Grain yield was obtained by separating spikelets from each sample, followed by threshing and cleaning grains using a column blower. Each whole biomass sample (including grains and chaff) was ground to pass a 2-mm screen in a Wiley mill for forage quality analyses. Total N concentrations were determined by analyzing gases evolved after flash combustion of samples in an auto-analyzer (Model Vario Macro, Elementar Ameericas, Inc., Mt. Laurel, NJ) and multiplied with a factor of 6.25 to calculate CP. The fractions of neutral detergent fiber (NDF) and acid detergent fiber (ADF) in forage samples were obtained by procedures outlined for a batch fiber analyzer (ANKOM Technology, Macedon, NY). In vitro true digestibility (IVTD) was determined by using procedures for a Daisy Digester (ANKOM Technology, Macedon, NY). Neutral detergent fiber digestibility (NDFD) was calculated by using the following equation (Hoffman et al., 2001):

$$\mathrm{NDFD} = [1-\{(100-\mathrm{IVTD})/\mathrm{NDF}\}] * 100$$

Data collected were analyzed by completely randomized design with three replicate sampled plots for each accession of finger millet. One-way analyses of variance (ANOVA) was performed on canopy height, dry biomass, grain yield, CP, NDF, ADF, IVTD, and NDFD using PROC GLM in SAS version 9.4 to identify the differences among accessions (SAS Institute, 2015). Differences among means were evaluated by

Least Significance Difference (LSD) test at 5% significance level (Steel and Torrie, 1980).

4.3. RESULTS AND DISCUSSION

4.3.1 Adaptability

All finger millet accessions showed excellent emergence (> 90%) despite some seeds being in storage for 36-53 years (Table 4.1.). Hence, finger millet seeds are capable of sustaining their germinability if held in storage for long periods of time. Finger millet seedlings showed good germination and establishment in the field after receiving three light irrigations in the first week and 120 mm rainfall the second week after transplanting (Figure 4.1.). However, a prolonged drought occurred afterward and only 30 mm of rain was received in the next seven weeks of June-July. All finger millet accessions exhibited moderate growth during the dry period and generated sufficient amounts of forage in response to precipitation that was received during the rest of the growing season. Average daily maximum temperature (Tmax) of 31˚C and minimum temperature (Tmin) of 18 ˚C were encountered during the growing season (Figure 4.2.). As finger millet is a short-day plant, requiring an optimum photoperiod of 12 hours (National Research Council, 1996), the possibility of flowering and grain formation during summers was not expected due to longer day lengths (about 14 hours). However, in this study, all of the finger millet accessions flowered and attained physiological maturity within 90-120 d after transplanting except PI 315700. In this study, the failure to flower by this accession was apparently related to its photoperiod sensitivity and source from a higher latitude (Table 4.1.).

4.3.2 Canopy Height

The canopy height of 11 finger millet accessions varied from 23-94 cm (Table 4.2.). The PI 462638 line showed maximum canopy height among the finger millets, while the minimum height was noticed in PI 315700 which had a spreading type growth form; both growth forms for these accessions were in agreement with the GRIN database (Table 4.1., 4.2.). In general, canopy heights of PI 462417, PI 462442, and PI 462943 were greater than those given in the GRIN database. Alternatively, PI 321083, PI 463041, PI 462414, PI 302662, and PI 321126 had shorter heights than the GRIN values (Table 4.1., 4.2.).

4.3.3 Grain Yield

Different accessions tested in this achieved grain yields that ranged from 60-1636 kg ha^{-1} during summer, in response to a common set of conditions (location, environment, soil fertility, row spacing, plant spacing, fertilizer level; Table 4.2.). The PI 302662 showed higher grain yields followed by PI 462414 and PI 262442, while the lowest grain yields were observed for PI 321126 and PI 462417. Grain yields of PI 321083, PI 462442, and PI 462414 matched the information stated by GRIN, while PI 462417, PI 463041, PI 462943, PI 462638, PI 321126, and PI 463012 were lower than the expected grain production scale of GRIN. In forage-livestock systems of the SGP, grain production of finger millet would not likely to play an important role. However, producers would need a seed source for planting if finger millet is to be a valid forage resource for this region. Growing varieties with a capacity for seed production would allow the use of finger millet in the SGP region, and perhaps result in an enhanced efficiency of farming operations. Moreover, with the continuously increasing human population, and demand for cereal grains, the grain-producing capacity of an accession used in the region may provide an opportunity for SGP producers to meet such future demands.

4.3.4 Forage Yield

The total dry biomass (including grain and chaff) produced by the finger millet accessions ranged between 5.0-12.3 Mg ha^{-1} (Table 4.2.). The greatest forage production was observed with PI 462638, which also achieved the tallest canopy height. In com parison, PI 462417, PI 315700, PI 462442, PI 462943, and PI 463012 showed lower forage production. The amount of forage produced by PI 302662 and PI 462638 was above the level stated by GRIN, while forage produced by PI 463041, PI 321126, and PI 315700 was below the expected levels; forage production by all remaining PI were in agreement with the GRIN database (Table 4.1., 4.2.). Overall, the quantity of forage produced by all finger millet accessions was above the level (1.1 Mg ha^{-1}) needed to avoid limitations on grazing by cattle due to forage availability (Coleman et al., 2010).

4.3.5 Nutritive value of forage

The CP, NDF, ADF, and IVTD concentrations differed among the 11 finger millet accessions (Table 4.3.). The CP content of finger millet accessions at 165 days after planting ranged from 105-156 g kg^{-1}. The highest concentrations of CP (130-156 g kg^{-1}) were observed in PI 462417, PI 462442, PI 321083, PI 462414, and PI 462943; CP was comparatively lower (105-126 g kg^{-1}) in the six remaining lines. The NDF concentration of the tested accessions ranged between 598-734 g kg^{-1}(Table 4.3.). The PI 321126 had the lowest NDF concentration, but was only different from PI 315700, PI 462638, PI 302662, and PI 462442. The ADF concentration of finger millet accessions varied from

268-382 g kg^{-1} (Table 4.3.). The lowest ADF concentration was observed in PI 462943, which was not different from those of PI 321083, PI 463041, PI 321126, and PI 463012. The IVTD of the accessions ranged between 597-730 g kg^{-1} (Table 4.3.). The higher IVTD concentrations (686-730 g kg^{-1}) were observed in PI 462943, PI 321126, PI 463012, and PI 321083 in comparison to the other seven finger millet lines. The NDFD of tested accessions varied from 387-552 g kg^{-1} (Table 4.3.). PI 462943 had the greatest amount of digestible NDF, though it was similar to those of PI 315700, PI 321083, PI 321126, PI 463012 and PI 463041. NDFD content is directly associated with the forage intake by cattle and a one-unit increase in NDFD leads to 0.17 kg/day increase in dry matter intake (Oba and Allen, 1999). It appeared that leaving the early maturing accessions in the field until harvest did not have a great effect on deterioration of dry matter or nutritive value. Consequently, finger millet could be left as standing forage until frost for grazing as needed based on depletion of other pastures.

Overall, PI 321083, PI 321126, and PI 462938 may be the three best candidates among the tested accessions for the SGP as these lines were able to produce 7.4-12.3 Mg ha^{-1} forage and grain yields of 897-1400 kg ha^{-1}. A general comparison of several forage nutritive value parameters from these three accessions with generalized attributes of bermudagrass and old world bluestem from other studies in Oklahoma is given in Table 4.4. However, soil and weather conditions varied among these and the current study, so some caution is required in these comparisons. The forage of finger millet at 165 days after planting appears superior to forage of both bermudagrass and old world bluestem in CP, NDF, and ADF. Therefore, finger millet has potential to produce quality summer forage, compared to the perennial warm-season grasses traditionally used as summer forage in the SGP.

While finger millet shows a degree of capacity to grow in the SGP, there are issues to be addressed before its use in the region, specifically the development of management strategies. There is little information regarding the optimum combination of row spacing, amounts of fertilizers, and water availability for the use of finger millet as both forage and grain crop in the SGP. The current limited availability of seed for the accessions tested here also means there is a need for seed increase to test the effects of different agronomic factors related to using finger millet as a forage crop at the plot scale. Further, there is need for information on the growth responses of finger millet in different soils of the region. The small seed size (1.3-1.6 mm) of finger millet also presents challenges for identifying the best technology for planting. Such issues must be addressed for application of finger millet in larger, production-scale settings for hay production and grazing in the SGP.

4.4. CONCLUSION

Finger millet accessions sourced from different geographic locations exhibited a range of adaptation to the summer conditions of the SGP. All finger millet lines tolerated the June-July hot and dry period and produced sufficient amounts of forage in response to precipitation that occurred during the rest of the growing season. All finger millet accessions, except PI 315700 which originated from South Africa, flowered and generated a wide range of grain yields which has not been previously reported for the U.S. within the existing literature. The grain-producing capability of finger millet may allow SGP producers to meet demands of gluten-free human food in the U.S. Finger millet forage possessed sufficient amounts of crude protein, lower fiber concentrations and higher digestibility at 165 days after planting than the traditional warm-season perennial grasses used to graze stocker cattle reported elsewhere, which indicates its potential for use in forage-livestock systems during summer in the SGP. Future research should focus on developing strategies for agronomic management and evaluating its capability in grazing and hay production systems for beef cattle.

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Table 4.1. Characteristics of ten finger millet accessions obtained from USDA-ARS Plant Genetic Resources Conservation Unit, as described by the Germplasm Resources Information Network (GRIN).

GRIN ID	Location	Latitude (°N)	Maturity (days)	Plant Height (m)	Foliage Amount	Seed yield	Year[2]
PI302662	India	31.10	108	0.9	Medium	Medium	1964
PI315700	South Africa	-25.73	106	0.3	Abundant	Medium	1966
PI321083	Kenya	-0.09	121	1.1	Abundant	Medium	1967
PI321126	Uganda	0.61	110	1.4	Abundant	Medium	1967
PI462414	India	22.98	112	0.8	Medium	Abundant	1981
PI462417	India	22.98	77	0.5	Medium	Abundant	1981
PI462442	India	25.09	87	0.3	Medium	Abundant	1981
PI462638	India	12.29	115	1.0	Medium	Abundant	1981
PI462943	Uganda	1.37	122	0.5	Medium	Medium	1981
PI463012	India	NA[1]	148	0.9	Medium	Medium	1981
PI463041	India	NA[1]	127	1.2	Abundant	Abundant	1981

https://npgsweb.ars-grin.gov/gringlobal/search.aspx (accessed 29 July 2018); [1]NA = Not Available; [2]Year in which the GRIN received seed

Table 4.2. Canopy height, total dry biomass, and grain yield of 11 accessions of finger millet at 165 days after planting when all accessions had completed reproduction at El Reno, OK.

GRIN ID	**Canopy Height (cm)**	**Total Dry Biomass (Mg ha^{-1})**	**Grain Yield (kg ha^{-1})**
PI 302662	77.0 c	10.53 b	1636.2 a
PI 315700	23.7 f	5.23 de	-
PI 321083	75.9 c	10.22 b	898.6 d
PI 321126	81.3 c	6.73 cd	60.2 g
PI 462414	57.0 e	7.40 c	1400.5 b
PI 462417	63.0 d	5.02 e	233.6 fg
PI 462442	61.7 de	5.40 de	1187.0 bc
PI 462638	94.1 a	12.35 a	1035.9 cd
PI 462943	66.7 d	6.48 cde	481.2 e
PI 463012	87.4 b	6.46 cde	313.9 ef
PI 463041	81.6 bc	6.93 c	392.5 ef
P-value	<0.0001	<0.0001	<0.0001
LSD (0.05)	5.7	1.50	233.9

Data are means of 3 replicates. Values within each column followed by same letter(s) are not different according to least significance difference (LSD) test ($P \leq 0.05$). NS = Non-significant at P=0.05.

Table 4.3. Forage nutritive value of whole plant biomass of 11 accessions of finger millet at 165 days after planting when all accessions had completed reproduction at El Reno, OK.

GRIN ID	**CP**	**NDF**	**ADF**	**IVTD**	**NDFD**
	-- ($g\ kg^{-1}$) ----------------------------				
PI302662	118.5 cd	675.2 b	366.6 ab	596.8 f	402.2 de
PI315700	105.5 d	733.9 a	382.3 a	648.1 cde	520.1 ab
PI321083	144.8 abc	613.0 de	294.2 def	685.7 abc	486.7 abc
PI321126	126.6 bcd	597.8 e	284.9 ef	701.3 ab	499.4 abc
PI462414	136.6 abc	641.2 bcde	335.9 bcd	631.3 def	423.1 cde
PI462417	156.4 a	634.7 bcde	340.5 abc	611.7 ef	387.4 e
PI462442	149.4 ab	657.4 bcd	353.8 ab	635.9 def	445.6 bcde
PI462638	121.3 bcd	670.0 bc	327.3 bcde	637.0 def	455.5 bcde
PI462943	130.3 acbd	600.6 e	268.4 f	730.5 a	551.8 a
PI463012	118.1 cd	607.1 de	291.6 def	691.8 abc	493.3 abc
PI463041	119.3 cd	620.0 cde	299.7 cdef	675.4 bcd	476.6 abcd
P-value	0.0398	0.0003	0.0003	<0.0001	0.0102
LSD (0.05)	29.2	50.4	44.7	45.4	81.8

Data are means of 3 replicates. Values within each column followed by same letter(s) are not different according to least significance difference (LSD) test ($P \leq 0.05$). NS = Non-significant at $P = 0.05$.

Table 4.4. Comparisons of forage nutritive value parameters of finger millet, bermudagrass, and old world bluestem.

Species	**CP**	**NDF**	**ADF**	**Citation**
	---------------------(g kg^{-1})	---------------		
Finger millet	134±24	641±42	319±37	
Bermudagrass	84±29	716±29	337±22	Starks et al., 2006
Old World bluestem	128±25	821±36	471±27	Ackerman et al., 2001

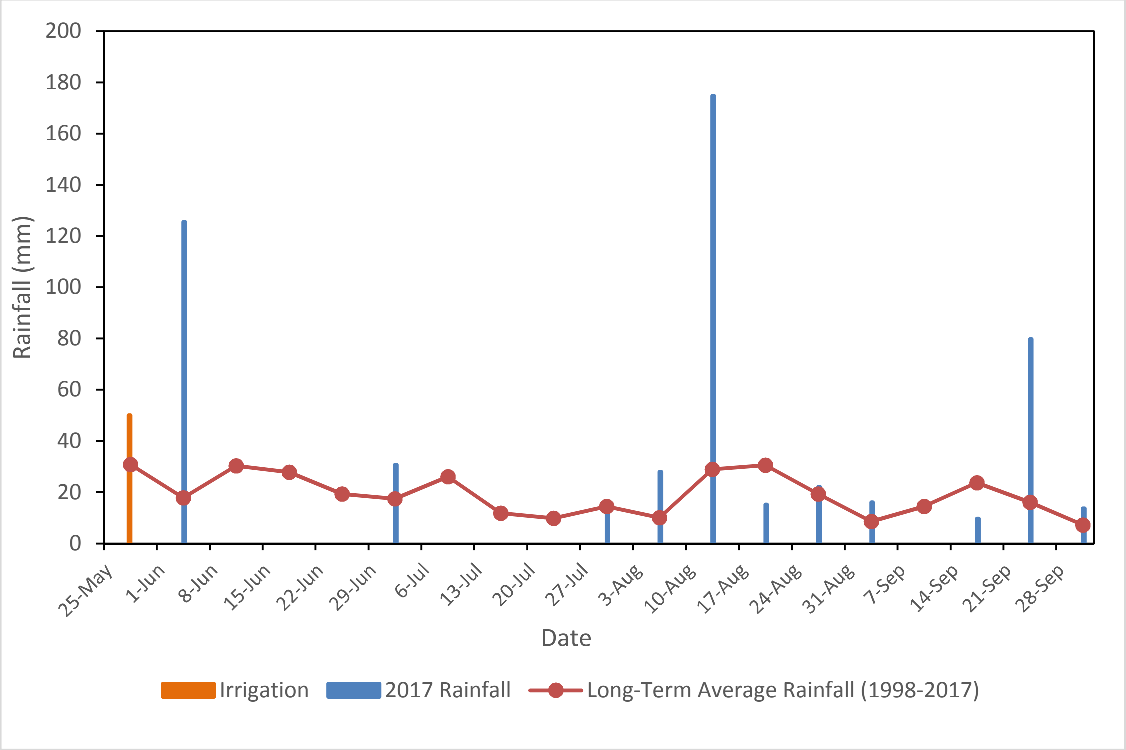

Figure 4.1. Weekly irrigation and rainfall received during the summer growing season of 2017 and the long-term trend in average rainfall (1998-2017) at El Reno, OK.

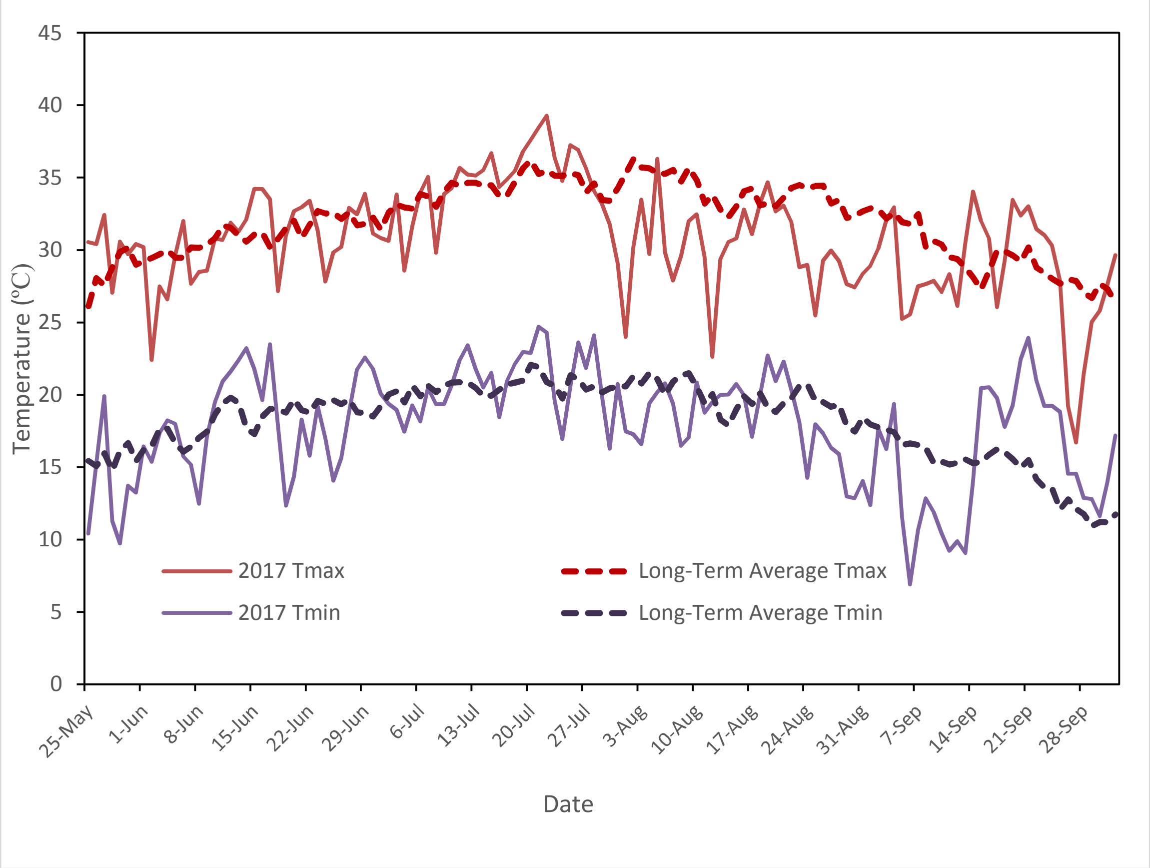

Figure 4.2. Daily temperature recorded during the summer growing season of 2017 and long-term averages (1998-2017) at El Reno, OK. Tmax and Tmin indicate the daily maximum and daily minimum temperatures, respectively.

CHAPTER V

COMPARING GROWTH AND PHYSIOLOGY OF THREE WARM-SEASON LEGUMES UNDER DIFFERENT WATER REGIMES

ABSTRACT

Prolonged drought periods are the major limitation to summer forage production in the Southern Great Plains (SGP). Drought-tolerant plants such as mothbean (*Vigna acontifolia*), tepary bean (*Phaseolus acutifolius*), and guar (*Cyamopsis tetragonoloba*) may serve as alternative summer forages and add resilience to the SGP's agricultural systems. However, information on the comparative response of these species to different water regimes is limited to identify the most reliable option. This greenhouse experiment was conducted to compare mothbean, tepary bean, and guar for their vegetative growth and physiological responses to four different water regimes: 100%, 75%, 50%, and 25% of field capacity (FC), applied from 27 to 77 days after planting (DAP). Tepary bean showed the lowest stomatal conductance (g_s) and photosynthetic rate (A), but it maintained the highest instantaneous water use efficiency (WUE_i) among species under 50% and 25% FC treatments. The A inhibitions were found to be mainly caused by

stomatal regulations in all three species under water deficit conditions. Despite maintaining higher A, growth rates of guar and mothbean were lower than tepary bean due to their limited leaf sink activity. At final harvest (77 DAP), the biomass yield generated by tepary bean was 38-60% and 41-56% higher than guar and mothbean, respectively, across water deficits. Tepary bean was identified as the most drought-tolerant and reliable option for SGP among the three tested species, considering its higher biomass production, WUE_i, leaf-to-stem ratio, and soil covering ability under a range of water regimes.

5.1. INTRODUCTION

Legume crops are an integral component of many cropping systems, and provide multiple services essential for agricultural sustainability. Besides delivering pulses (grains) for humans and forage for livestock, legumes add organic nitrogen to the soil, provide cover to reduce runoff and soil erosion, mitigate greenhouse gas emissions, and increase carbon sequestration (Stagnari et al., 2017). The continuous rise in prices for inorganic nitrogen fertilizers has stimulated growers to incorporate legumes as grain, forage, or green cover into different cropping systems in many countries, including the United States (US). Although legumes utilized as either forage or green cover result in lower biomass yields than cereals, they provide higher N contents and more digestible herbage for livestock (Rao et al., 2005).

Forage-livestock production systems used in the US Southern Great Plains (SGP) largely depend on winter wheat (*Triticum aestivum* L.) during fall through spring, and on perennial grasses such as old world bluestems (*Bothriochloa* spp.), bermudagrass [*Cynodon dactylon* (L.) Pers.], or native prairie during summer for grazing stocker cattle

(Coleman and Forbes, 1998; Phillips and Coleman, 1995; Phillips et al., 2003; Baath et al., 2018a). However, available forage provided by these perennial grasses often show a decline in their yield and nutritive value by mid-summer, which can limit the rate of weight gain in stockers if not supplemented with expensive protein diets (Philips and Coleman, 1995). Therefore, the potential of novel grain legumes in providing good amounts of quality forage while increasing soil nitrogen levels need to be investigated to improve the sustainability of forage-stocker production systems.

Research work conducted in the SGP over the last two decades has focused on defining the forage and green cover potential of several grain legumes (Northup and Rao, 2015; Rao et al., 2002; Rao and Northup, 2009, 2012, 2013). Some of the tested grain legumes, such as pigeon pea [*Cajanus cajan* (L.) Millsp.], could provide high N biomass. However, the value of many pulses for grazing may also be limited due to the presence of larger, less-digestible stems in aboveground biomass (Rao and Northup, 2012; 2013), and the presence of condensed tannins in plant tissues, that inhibit grazing (Price et al., 1980). Such issues, in addition to effects on soil water and other resources important to the productivity of winter wheat have resulted in a continuing exploration of the pulses of the world to identify novel species that may function as high-quality forage.

Recent research has identified two novel pulses with potential to serve as forage: tepary bean [*Phaseoulus acutifolius* (A.) Gray]; and mothbean [*Vigna aconitifolia* (Jacq.) Marechal]. Both pulses drew attention due to herbage with high N contents and fiber digestibility, and plant canopies with fine stems (Baath et al., 2018b; Baath et al., 2018c; Bhardwaj, 2013). Further, guar [*Cyamopsis tetragonoloba* (L.) Taub.], a true multi-purpose pulse with industrial uses (Whistler and Hymonitz, 1979; Sainy and Paroda, 1997), also has the capacity to produce digestible, high-N biomass when harvested during the vegetative growth phase (Rao and Northup, 2013).

The selection of alternate crop species for summer periods in the SGP is critical, as agricultural production is largely rain fed, and the agro-climatic conditions of the region are highly variable. The region often experiences prolonged droughts, and the amount of summer precipitation received is highly erratic on a yearly basis (Schneider and Garbrecht, 2003). Therefore, it is essential to identify drought-tolerant crops capable of producing significant yields, with minimal amounts of moisture, under the variable climatic conditions of the SGP. Tepary bean, mothbean, and guar are known for drought tolerance in their native regions (Baath et al., 2018b) and have the potential to serve as summer crops in rotation with winter wheat in the SGP. However, an understanding of the comparative response of their vegetative growth to a range of water regimes is essential to determine their adaptability to the SGP.

Reduction in transpiration rate (*E*) under stomatal regulation is a typical response of most plants to water stress, which allows them to increase their water use efficiency (WUE). Some species tolerate water stress better than others by partially closing their stomata at higher water potentials, and hence become more efficient at utilizing available water under drought conditions (Markhart, 1985). However, the reduction in stomatal conductance (g_s) under severe water stress can cause an imbalance between electron transport required for photosynthesis (*A*) and photochemical activity in photosystem II, and thus lead to photosynthetic inhibition (Singh and Reddy, 2011). As growth rates of plants are generally determined by rates of photosynthesis (*A*), an association of higher *A* and improved WUE may result in yield enhancement under conditions of water stress

(Parry et al., 2005). Therefore, a comparison of physiological responses is necessary to understand how these crop species deal with different levels of drought stress. The objectives of this study were to; (1) compare mothbean, tepary bean and guar for their vegetative growth responses to four water regimes, and (2) analyze the effects of water stress on their physiological processes.

5.2. MATERIALS AND METHODS

5.2.1. Plant culture and experimental conditions

The experiment was carried out in a greenhouse setting at the Oklahoma State University, Stillwater, OK (36.12 °N, 97.06 °W) during the spring season of 2018. Seeds of tepary bean cv. PT082 (*Native Seeds*, Tucson, Arizona, USA), guar cv. Matador (*Guar Resources*, Brownfield, Texas, USA), and mothbean cv. PI426980 (*Plant Genetic Resources Conservation Unit*, Griffin, Georgia, USA) were sandwiched within moistened paper towels and kept at 28 °C for two days to induce germination. Seeds showing radicle emergence were planted in polyvinylchloride pots (0.75 m tall, 0.15 diameter), which were filled with gravel at the bottom to allow drainage of excess water, and the remainder of tubes were packed with pure, fine mason sand. The applied photoperiod was extended to 14 hours' using supplemental lighting provided by a combination of metal halide and high-pressure sodium lamps. Temperature maintained inside the greenhouse was recorded every three minutes using a data logger (TP425, The Dickson Company, Addison, IL). The average day and night temperatures observed during the experiment period were 30.2±7.8 and 21.3±5.1°C, respectively.

5.2.2. Water deficit treatments

Plants of all three species were allowed to grow until 77 days after planting (DAP). During the initial four weeks after planting, full-strength Hoagland nutrient solution was applied to every pot three times a day (0800, 1200, and 1600h) by an automated drip irrigation system that used a timing device to supply all plants with optimum water and nutrient conditions. The duration of irrigation events by the system was adjusted to maintain soil moisture at field capacity (FC; 0.08-0.10 $m^3\ m^{-3}$), which was monitored using TDR moisture probes (MiniTrase, Soilmoisture Equipment Corp., Santa Barbara, CA). At 27 DAP, four different water treatments were randomly applied to thirty-two plants each, and continued until final harvest at 77 DAP (Figure 5.1.). Among water treatments, the 100% field capacity (FC) treatment continued to receive full irrigation as a control, and three deficit treatments were assigned to other sets of plants; 75% FC (mild water stress), 50% FC (moderate water stress), and 25% FC (severe water stress) using timing devices.

5.2.3. Growth measurements

Four plants were randomly sampled from each treatment combination at 48, 62, and 77 DAP**.** The number of leaves was counted on each plant, and leaf area was determined with an LI-3100 leaf meter (LI-COR Inc., Lincoln, NE). Each sampled plant was harvested and partitioned into leaves (including pods when encountered) and stems, and oven-dried at 65 °C to a constant weight, to determine dry weights of leaves and stems, and leaf-to-stem ratios. The sum of dry weights of leaves and stems was identified as total aboveground biomass. The rates of main stem elongation, leaf addition, leaf growth, stem growth, leaf area expansion and biomass accumulation were estimated from length of main stem, number of leaves, leaf weight, stem weight, leaf area and dry biomass weight, respectively, observed on the three sampling dates.

5.2.4. Physiological measurements

The gas exchange and chlorophyll fluorescence parameters were recorded using an LI-6400 photosynthesis system (LI-COR Inc., Lincoln, NE) on the third or fourth fully expanded leaves of plants between 11:00 and 13:00 h at 55 DAP. The instrument was set to the photosynthetic photon flux density of 1200 µmol photon m^{-2} s^{-1}, cuvette temperature of 32 °C, relative humidity of 35 ± 5%, and CO_2 concentration of 400 µmol mol^{-1}. Each measurement was logged when a steady-state was achieved. The quantum efficiency by open photosystem II reaction centers oxidized in light was determined as:

$$\frac{Fv'}{Fm'} = \frac{Fm' - Fo'}{Fm'} \qquad Eq.[1]$$

where Fm' and Fo' are maximum and minimum fluorescence, respectively, achieved in light-adapted leaves (DaMatta et al., 2002). The electron transport rate (ETR) was calculated based on the equation (Kakani et al., 2008):

$$ETR = [(Fm' - Fs)/Fm')]\, fI\alpha_{leaf} \qquad Eq.[2]$$

where Fs is steady-state fluorescence, f is the fraction of absorbed quanta used by photosystem II, *I* is incident photon flux density, and α_{leaf} is leaf absorptance. Instantaneous water use efficiency (WUE_i) was estimated as the ratio of *A* and *T*. The ratio of ETR/A was used to estimate the number of electrons required to fix one CO_2 molecule.

5.2.5. Statistical analysis

The experimental pots were arranged in a strip-plot design, with water treatments treated as the whole plots and legume species as strip plots. The relationship between (ratio of intercellular to ambient CO2 concentrations (C_i/C_a) and g_s was tested for linear, polynomial, and exponential function, and the best regression was selected based on coefficient of determination (r^2) for each species. The relationships of g_s with Fv'/Fm' and ETR were described by an exponential rise three-parameter regression function, [$Y = y0 + (a * \exp^{bx})$]. An exponential decay three-parameter function, [$Y = y0 + (a * \exp^{-bx})$], was used to describe relationship between ETR/A and g_s. Elongation rates of main stems, leaf addition, leaf growth, stem growth, leaf area expansion and biomass accumulation were calculated as the slope of a linear regression between observed values and days after the onset of water treatments using PROC REG in SAS 9.4 (SAS Institute, 2017). The relationship among the water levels and estimated growth rates were fitted with second-order polynomial function, ($Y = y0 + ax + bx^2$). All regression analyses were conducted using SigmaPlot version 14 (Systat Software Inc., San Jose, CA). Physiological parameters, involving A, g_s, T and WUE_i, and growth parameters determined at final harvest were subjected to two-way analysis of variance (ANOVA) using PROC GLM in SAS 9.4 (SAS Institute, 2017). After significant water x species interaction were noted at $p \leq 0.05$, species treatments were tested at each individual water treatment using one-way ANOVA, and their means were separated using the Fisher's least significant difference (LSD) comparison at $p \leq 0.05$.

5.3. RESULTS

5.3.1. Physiological responses

All three species showed significant reductions in g_s with increasing amounts of water deficit (Figure 5.2a), but differed in intensity of their individual responses ($p \leq 0.05$) across the four water treatments. Tepary bean had the lowest observed g_s under all levels of water deficit, though it was not significantly different ($p > 0.05$) from guar at 75% FC treatment. Mothbean had the highest g_s at 100% FC, but showed responses that were similar to guar under the three other water treatments. The rates of A and T of all three species declined substantially as water deficit increased (Figure 5.2b; Figure 5.2c). The decline in T followed similar patterns to g_s, while A was not entirely proportionate to g_s. The greatest A was exhibited by guar under the different water treatments, but was not significantly different ($p > 0.05$) from mothbean at 25% FC and 100% FC. Alternatively, tepary bean showed the lowest A among species across all four levels of water deficit, though a comparable response was observed for mothbean at 75% FC.

Tepary bean exhibited 43% and 45% higher WUE_i than mothbean and guar, respectively, under the most-severe water stress (25% FC; Figure 5.2d). Likewise, at 50% FC treatment, it was 39% and 29% higher than mothbean and guar, respectively. In contrast to tepary bean and mothbean, guar did not show larger reductions in WUE_i with increasing water availability. Thus, the WUE_i of guar was consistent and comparable to tepary bean, and higher than mothbean under 75% and 100% FC treatments.

Different responses of C_i/C_a ratio were observed with reducing g_s in all species, though all declined and none showed increases at the lowest observed values of g_s

(Figure 5.3a). A linear relationship of C_i/C_a with g_s was obtained for guar ($r^2 = 0.86$), while mothbean and tepary bean showed a quadratic ($r^2 = 0.88$) and exponential ($r^2 = 0.94$) responses, respectively. In comparison to their C_i/C_a responses, both guar and mothbean showed an exponential decline in Fv'/Fm' with reduction in g_s, with guar showing a steeper slope for the relationship (Figure 5.3b). No significant change ($p > 0.05$) in Fv'/Fm' was depicted by tepary bean in response to stomatal closure, although Fv'/Fm' values were generally lower, compared to mothbean and guar.

All three species depicted an exponential decline in ETR with decrease in g_s under water stress (Figure 5.3c). The ETR in guar remained comparatively high under well-watered or mild water stresses ($0.22 < g_s < 0.45$) compared to tepary bean and mothbean, but was comparable to both under moderate to severe water stress. Tepary bean maintained a slightly higher ETR than the other pulses at g_s ranging between 0.0 and 0.1. The ETR/A value increased at a similar fashion for all three species with decline in g_s until 0.1 μmol H_2O m^{-2} s^{-1} (Figure 3d). Once g_s was below 0.1 μmol H_2O m^{-2} s^{-1}, tepary bean had a significantly higher ETR/A compared to mothbean and guar.

5.3.2. Vegetative growth responses

Rates of mainstem elongation were influenced by water stress in guar and mothbean, but was minimally effected in tepary bean (Figure 5.4a). Both guar and mothbean showed an increase in the rate of mainstem elongation with increasing available water, with greatest rates (~2.1 cm d^{-1}) observed at 100% FC treatment. Further, similar rates of mainstem elongation (1.9-2.0 cm d^{-1}) were exhibited by mothbean and guar at 75% FC, while responses varied at 25% and 50% FC. Guar had a higher rate of main stem elongation at 25% FC, but was surpassed by mothbean at 50% FC treatment. In comparison, tepary bean showed low rates of mainstem elongation under all water deficit treatments.

The growth rates of stems for all species did not follow trends that were similar to rates of mainstem elongation (Figure 5.4b). All three species depicted approximate stem growth rates (0.04-0.05 g d^{-1}) at 25% FC. However, mothbean accumulated less stem weights at 50, 75, and 100% FC than guar or tepary bean. Rates of stem growth in both guar and tepary bean showed a similar increase with increasing water availability, with a slightly higher rate of stem growth for tepary bean under the control treatment.

Rates of leaf addition for all three legumes increased substantially as water availability increased (Figure 5.4c). Tepary bean showed the greatest rates of leaf addition, while guar showed the lowest rates under all applied treatments. Rates of leaf addition by tepary bean (5.6 leaves d^{-1}) were substantially higher than mothbean (2.1 leaves d^{-1}), and guar (0.9 leaves d^{-1}) under 100% FC (control) conditions. At 25% FC, the rate of leaf addition for tepary bean (1.1 leaves d^{-1}) was 115% and 313% higher than in mothbean and guar, respectively.

The rate of expansion of leaf area in mothbean and tepary bean were comparable under the 25% FC and 50% FC treatments (Figure 5.4d). While in congruence with observed rates of leaf addition, tepary bean showed the greatest rates of leaf expansion at 75% and 100% FC (88.4 cm^2 d^{-1} and 63.0 cm^2 d^{-1}, respectively). The lowest rates of expansion of leaf area among species were observed for guar, which ranged between 22.7 cm^2 d^{-1} at 25% FC and 26.9 cm^2 d^{-1} at 100% FC water treatment.

The growth rate of leaves increased with increasing amounts of available water for all three species, though tepary bean had numerically greater responses (Figure 5.4e). Mothbean and guar showed comparable rates of leaf growth, varying from 0.06 g d^{-1} at 25% FC to 0.25 g d^{-1} at 100% FC. In contrast, leaf growth of tepary bean was steeper, with rates of 0.29 and 0.41 g leaves d^{-1} observed at 75% FC and 100% FC, respectively.

As with rates of growth by leaves and stems, the rate of accumulation of aboveground biomass was consistently higher for tepary bean compared to mothbean and guar under all water deficit levels (Figure 5.2f). Tepary bean resulted in the greatest biomass accumulation rate (0.89 g d^{-1} at 100% FC), which was 37% and 53% higher than rates for mothbean and guar, respectively. Tepary bean also produced biomass at rates that were 80% and 107% higher than mothbean and guar, respectively, under the 25% FC treatment.

5.3.3. Final harvest

The total number of leaves per plant formed by the three legume species differed significantly ($p \leq 0.05$) when compared across the four water treatments at 77 DAP (Figure 5.5a). Tepary bean had 251.2 leaves $plant^{-1}$ under 100% FC, which was distinctly higher than guar (37.2 leaves $plant^{-1}$), and mothbean (89.5 leaves $plant^{-1}$). Additionally, tepary bean largely exceeded guar and mothbean in the number of leaves at 75%, 50%, and 25% FC. Guar had the least number of leaves per plant under all water treatments, though it was not statistically different from mothbean at 75% and 100% FC treatments. Similar results were observed among the species for leaf area under each water treatment (Figure 5.5b). Tepary bean resulted in 1.8-2.7 and 3.5 times more leaf area than mothbean and guar, respectively, across the different water levels. Among species, guar showed the lowest leaf area per plant, which ranged between 319 cm^2 at 25% FC and 1416 cm^2 at 100% FC. Although mothbean had comparatively higher leaf area than guar at all water deficit treatments, a statistical difference between mothbean and guar was only observed at 50% FC.

Significant differences were observed among the legume species for leaf weight per plant in every water treatment (Figure 5.5c). Among species, tepary bean had the greatest leaf weights in all four water deficit treatments. Guar and mothbean showed similar leaf weights; and both generated half leaf weight of tepary bean for all water deficit treatments. Alternatively, stem weight per plant did not follow the same trend as leaf weight per plant (Figure 5.5d). Although the greatest amount of stems was produced by tepary bean, it was not significantly different from guar at 75% and 100% FC. Mothbean generated the least amount of stem weights across all four water treatments, but was similar to responses by guar at 25% and 50% FC. However, the leaf-to-stem ratios obtained for tepary bean were higher and ranged between 2.5 and 4.5 at 100% and 25% FC treatment, respectively (Figure 5.5e). The leaf-to-stem ratio of mothbean was comparable to tepary bean, while guar generated the smallest leaf: stem ratios in response to each of the four water treatments.

The amounts of aboveground biomass were significantly higher for tepary bean than those of guar and mothbean across all four water treatments (Figure 5.5f). Tepary bean produced 38-60% and 41-56% greater biomass yields than guar and mothbean, respectively, under the different water deficits used in the study. In comparison to the potential biomass yield observed under 100% FC (control), tepary bean showed a reduction of only 8% at 75% FC, while guar and mothbean were reduced by 24% and 13%, respectively. Similarly, under severe water deficit (25% FC), the decline in biomass produced by tepary bean was reduced 60%, compared to 70% and 74% reductions for mothbean and guar.

5.4. DISCUSSION

Due to the sensitivity of g_s to most of the internal and external factors linked to drought, it serves as an integrative basis to understand the influence of water stress on photosynthetic parameters (Singh and Reddy, 2011). The stomatal regulated reductions in A and T vary within species and thus allow some plant species to better tolerate water stress (Klein et al., 2013). Similarly, the three legume species evaluated differed in their stomatal behavior, and therefore resulted in different growth and production responses on exposure to the range of water regimes used in this study. Declines in g_s occurred in each of three species with increasing water stress, but tepary bean showed greater g_s reductions than mothbean and guar under moderate (50% FC) and severe (25% FC) water treatments. Markhart (1985) also reported a greater stomatal closure in tepary bean compared to common bean (*Phaseolus vulgaris* L.) across different water deficit levels. Therefore, the amount of water losses through T was better controlled by tepary bean than either mothbean or guar under water-stressed conditions (25% and 50% FC).

Although tepary bean showed a greater decline in A due to lesser g_s, WUE_i was substantially higher than either guar or mothbean. In contrast, the g_s of mothbean was significantly higher under mild (75%) water-stressed and well-watered (100%)

conditions. Consequently, mothbean was the least water efficient among three the species due to its greater loss of water through *T* and a moderate increase in *A*. While the increase in *A* was proportional to increasing *T* in guar under the three water levels of deficit, there was little change in instantaneous WUE_i.

Other than *A* limitations caused by reductions in g_s, non-stomatal limitations could also occur due to photodamage of PSII for over-excitation under severe water-stressed conditions (Gururani et al., 2015). The occurrence of non-stomatal limitation is generally related to an increase in C_i/C_a at low g_s under severe water-stressed conditions (Brodribb, 1996; Souza et al., 2004). While a low g_s was only observed in tepary bean in this study, and it did not cause increases in C_i/C_a under the severe water-stressed treatment (25% FC). Since WUE is inversely related to the C_i/C_a ratio, the lower values of C_i/C_a obtained with tepary bean at $g_s < 0.1$ also revealed an ability to maintain higher WUE compared to guar and tepary bean under severe water stress (Singh and Reddy, 2011). Additionally, no significant change in F_v'/F_m' and a higher ETR were observed, which suggested that the PSII system of tepary bean was less susceptible to photo-damage under severe water stress, compared to the other tested species.

Although all three species down-regulated their photosynthetic ETR, and an increase in ETR/A was observed with increasing water stress, a large difference in consumption of electrons for CO_2 fixation was observed in tepary bean under severe water stress. This implies an increased activity of alternative electron sinks, such as photorespiration, to handle excess electrons generated by photosynthesis (Guan and Gu, 2009); however, it also suggests the potential risk of oxidative damage by reactive oxygen species in tepary bean (Palliotti et al., 2015). A higher Fv'/Fm', and maintenance of ETR in guar indicates a greater photochemical efficiency under mild water stress or well-watered conditions compared to mothbean and tepary bean. However, guar showed a rapid decline in Fv'/Fm' and ETR at increased water stress, which suggested the downregulation of PSII activity with photo-protective mechanisms such as non-photochemical quenching or increase in thermal energy dissipation (Subrahmanyam et al., 2006). Likewise, the PSII activity was downregulated in mothbean with the decrease in g_s, though the responses of Fv'/Fm' and ETR remained lower compared to guar. Nevertheless, there was no evidence of non-stomatal limitation, and *A* inhibition could be assumed mainly due to stomatal regulation in all three species.

Rates of plant growth and carbon assimilation are intimately associated, but the extent to which *A* increases plant growth depends on the activity of sinks (Tardieu et al., 2011). In many cases, water stress was found to uncouple *A* and plant growth as carbon assimilation is maintained while sink activity is affected (Muller et al., 2011). Similarly, guar and mothbean maintained higher *A*, while their growth rates were lower due to limited sink activity compared to tepary bean under the two treatments that caused the greater water-stress (25% and 50% FC). In contrast, tepary bean maintained a higher rate of leaf addition despite lower A, and resulted in greater biomass accumulation than guar and mothbean across all levels of water stress. Additionally, greater biomass production in tepary bean could also be attributed to its early vigor and greater WUE_i under water-stressed conditions (Condon et al., 2002; Ludwig and Asseng, 2010).

Tepary bean demonstrated lower rates of main stem elongation compared to guar and mothbean across all water levels, which was mainly due to its vining, more spreading, growth habit, consisting of numerous secondary and tertiary stems. Accordingly, the stem growth rate and final stem weight of tepary bean were similar or higher compared to guar in spite of lower rates of elongation by main stems. However, the leaf growth rate and final leaf weight of tepary bean were greater than guar or mothbean, which can be related to its greater rates of leaf addition and leaf area expansion. Thus, tepary bean not only resulted in greater biomass production but also higher leaf-to-stem ratio than guar across all water treatments.

In terms of forage use, leaves of legumes are generally highly nutritious relative to stems, while contain higher cell wall fractions (Foster et al., 2009). Legume species with a low leaf-to-stem ratio are assumed to cause limitation to animal forage intake due to low biomass digestibility. Therefore, the leaf-to-stem ratios ranging between 2.5-4.5 observed for both tepary bean and mothbean indicated their potential as sources of superior forage quality compared to other known legume forages (Rao et al., 2003; Foster et al., 2009; Rao and Northup, 2013). However, a comparatively higher proportion of inferior quality stem generated by guar could limit its value for grazing (Rao and Northup, 2009; 2013). Furthermore, tepary bean possessed higher rates of leaf area expansion and resulted in greater amounts of leaf area per plant more rapidly than guar or mothbean across all water regimes through final harvest. Thus, the capability of tepary bean to generate high leaf biomass indicates this species may have higher value as a green cover or forage crop than guar or mothbean.

5.5. CONCLUSION

Stomatal conductance was the main limitation to A in all three species under water deficit conditions, and there was no evidence of non-stomatal limitation in the current study. Tepary bean tolerated water stress better than mothbean and guar due to its greater stomatal closure and WUE_i, coupled with greater vigor and higher sink activity during early stage of seedling development. Consequently, tepary bean possessed the highest growth rate and generated the greatest aboveground biomass across all water levels. Growth rates observed for mothbean and guar were similar, though a comparatively higher leaf-to-stem ratio was obtained in mothbean. High leaf-to-stem ratio noticed in both tepary bean and mothbean suggested their potential superior forage quality compared to guar. Further, the greater leaf area noted for tepary bean observed across all water deficits indicates that it may also have high value as a cover crop capable of reducing soil erosion, suppressing weeds, and improving soil health. Overall, tepary bean would be the most reliable choice for further investigation in SGP conditions among the tested species, considering its greater biomass production, WUE_i, leaf-to-stem ratio, and soil covering ability under a range of water regimes. Furthermore, there is need to investigate soil-root dynamics and soil water extraction patterns at field levels within these species, when grown as a summer crop in rotation with winter wheat.

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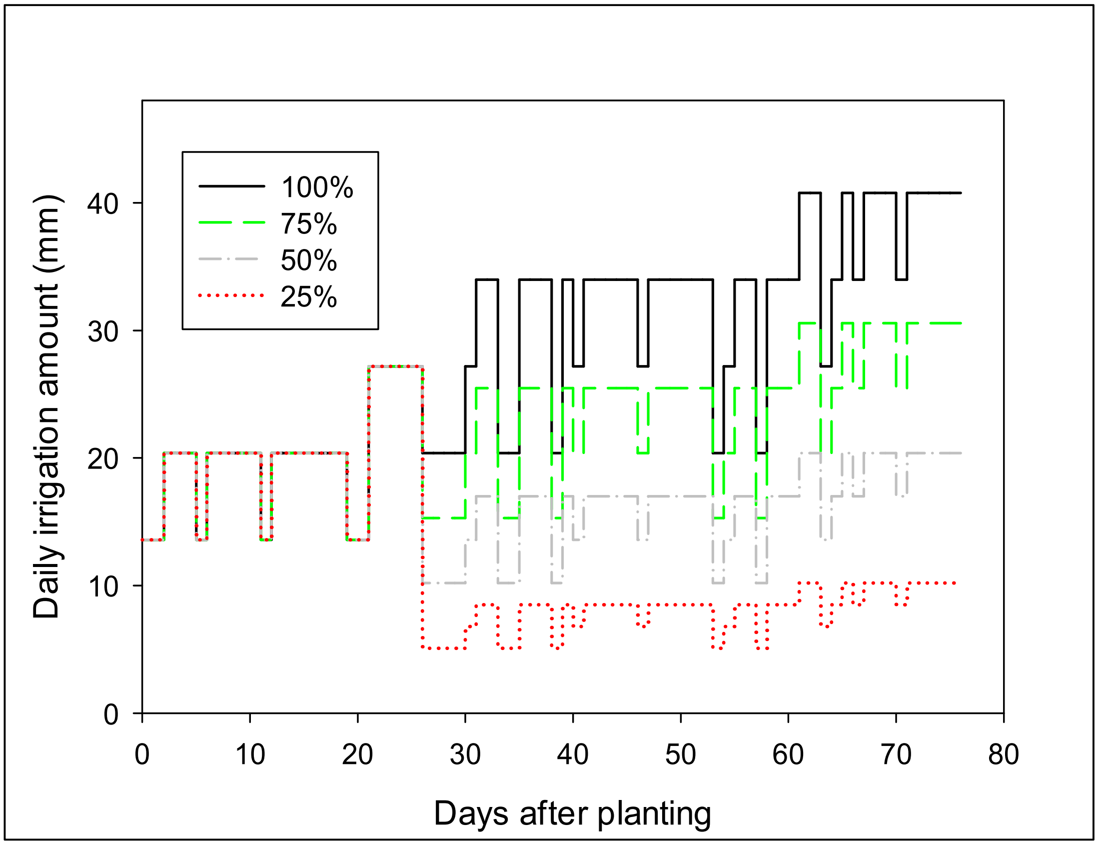

Figure 5.1. Daily irrigation amount (mm) applied in four water treatments during the growing season.

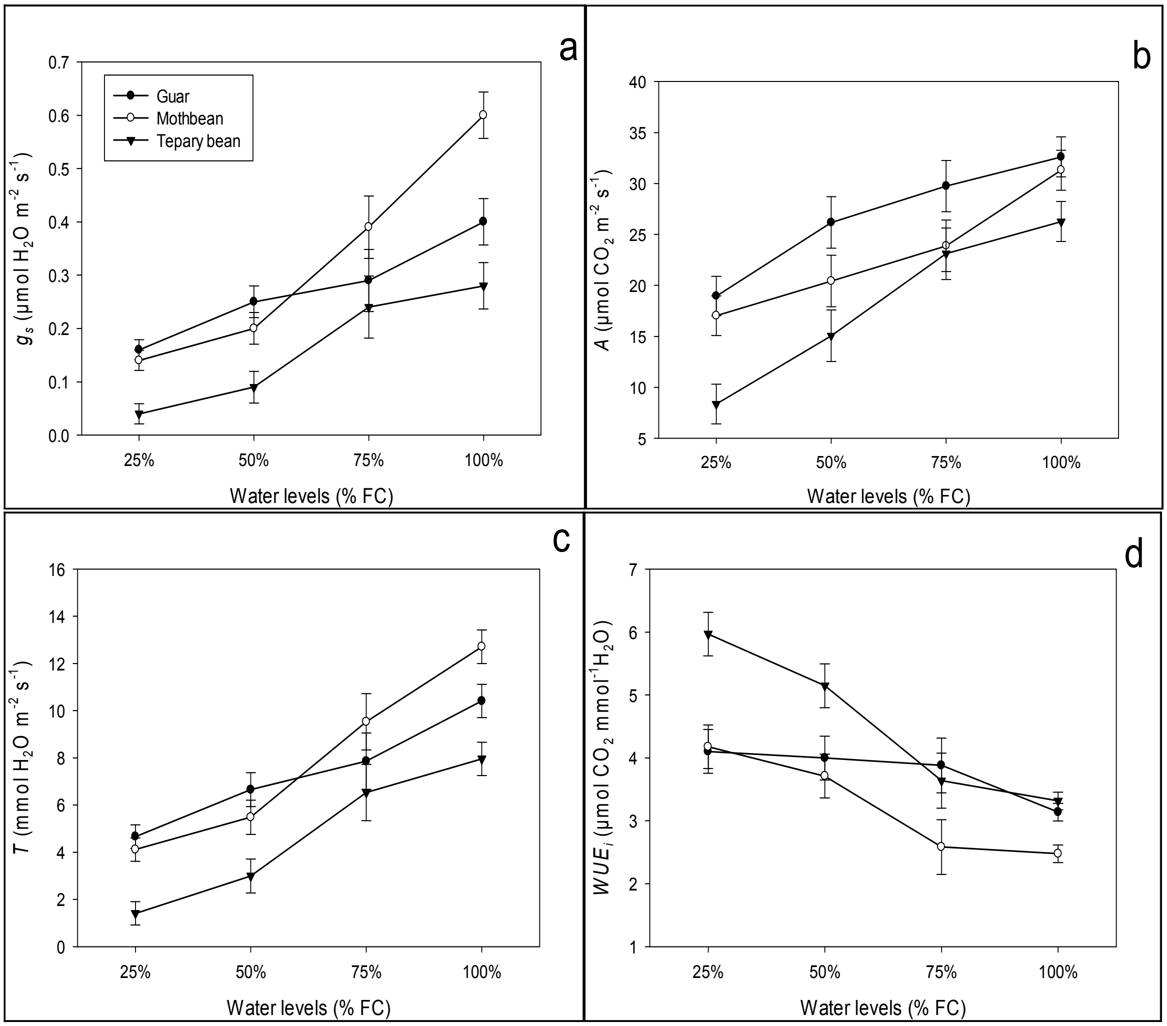

Figure 5.2. Effect of four water deficit treatments on (a) stomatal conductance (g_s), (b) net photosynthetic rate (A), (c) transpiration rate (T), and (d) instantaneous water use efficiency (WUE_i) in three warm-season legume species. Error bars are standard errors derived from one-way analysis of variance.

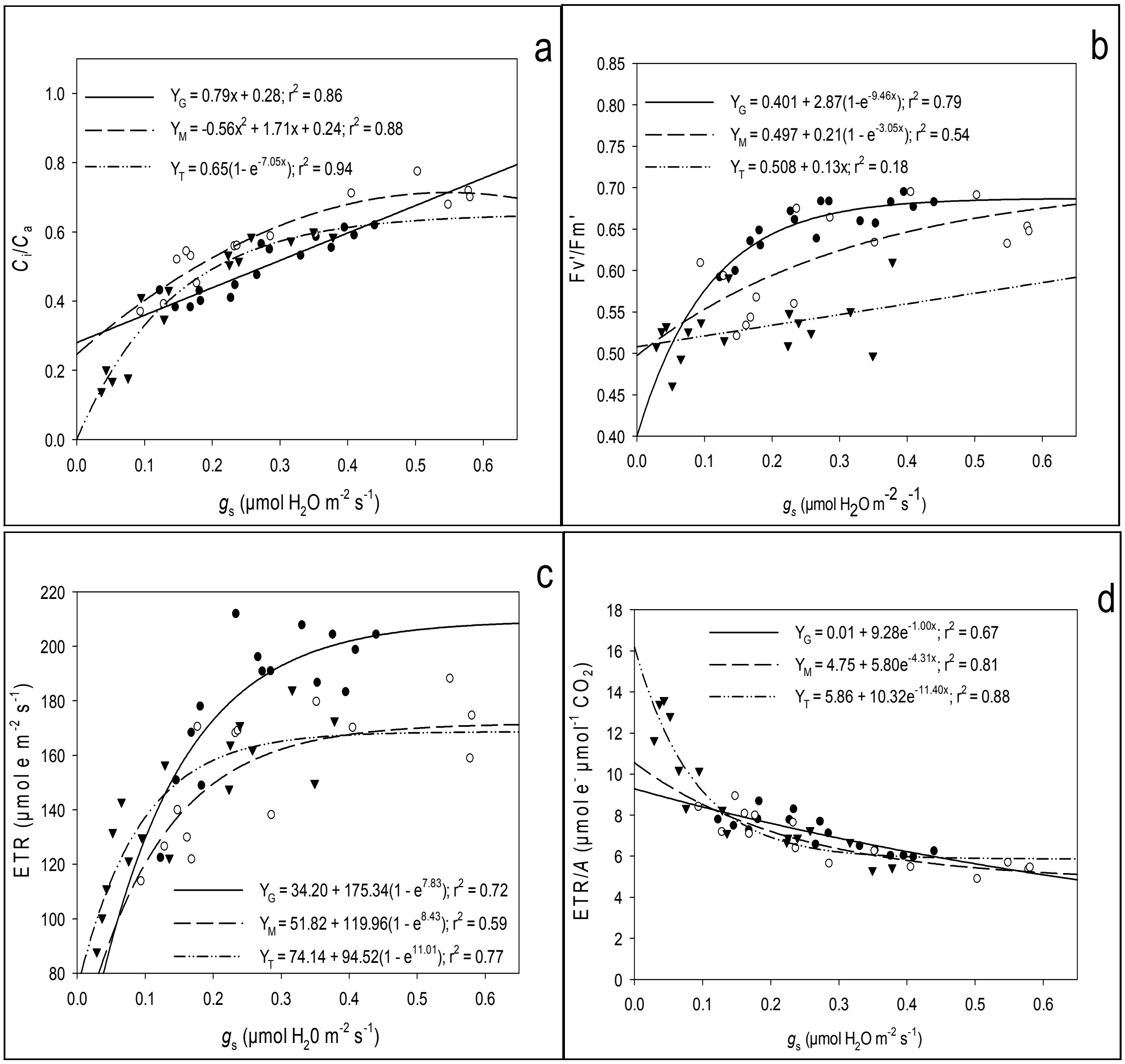

Figure 5.3. Relationships between stomatal conductance (g_s) and (a) C_i/C_a ratio, (b) fluorescence (Fv'/Fm'), (c) electron transport rate (ETR) and (d) ETR/*A* ratio for three warm-season legume species. Closed triangles (▼) represent data from tepary bean (T), and open (○) and closed (●) circles represent data from mothbean (M) and guar (G), respectively.

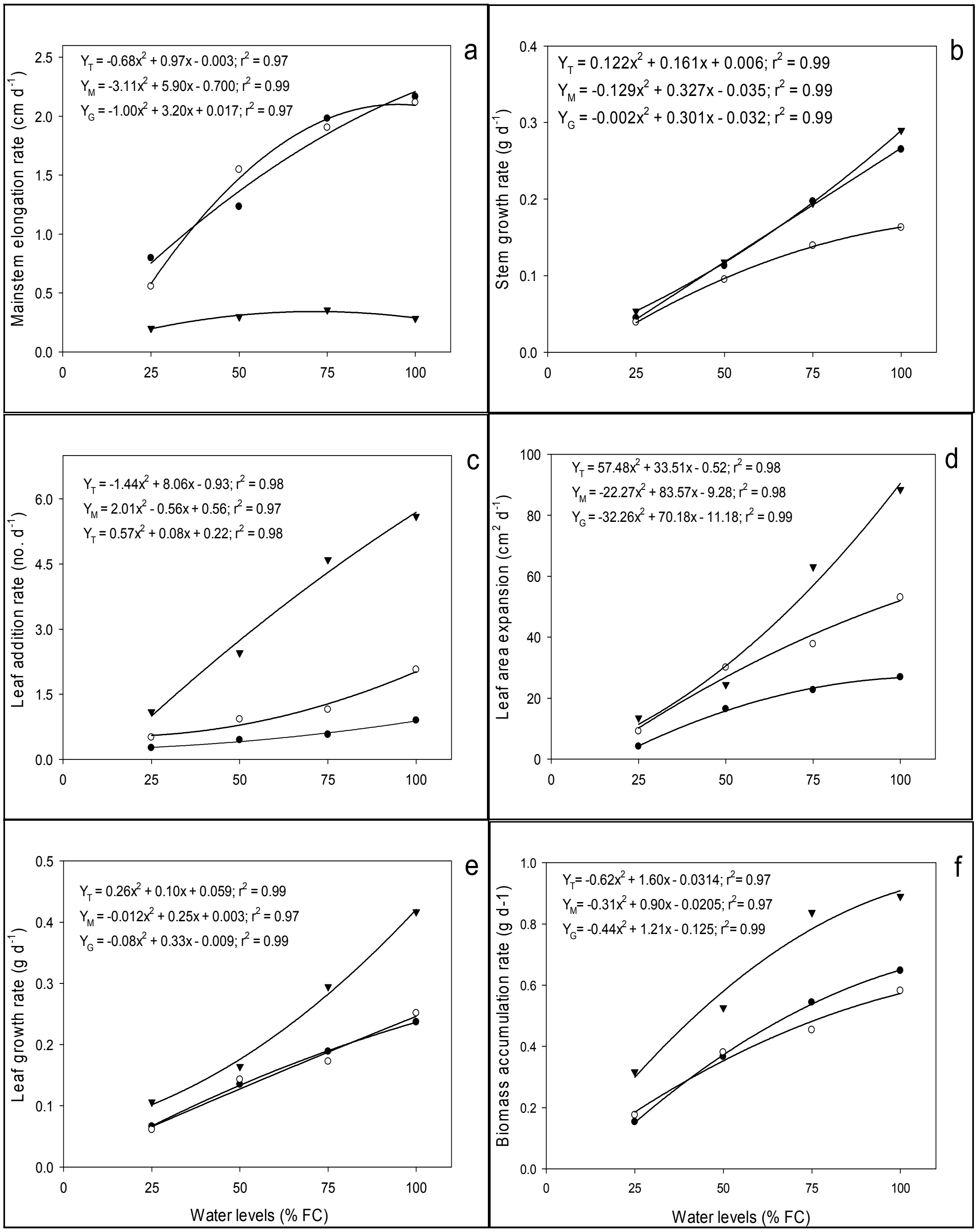

Figure 5.4. Influence of soil water deficit on (a) mainstem elongation rate, (b) stem growth rate, (c) leaf addition rate, (d) leaf expansion rate, (e) leaf growth rate, and (f) biomass accumulation rate of three warm-season legumes. Closed triangles (▼) represent data from tepary bean (T) , and open (○) and closed (●) circles represent data from mothbean (M) and guar (G), respectively.

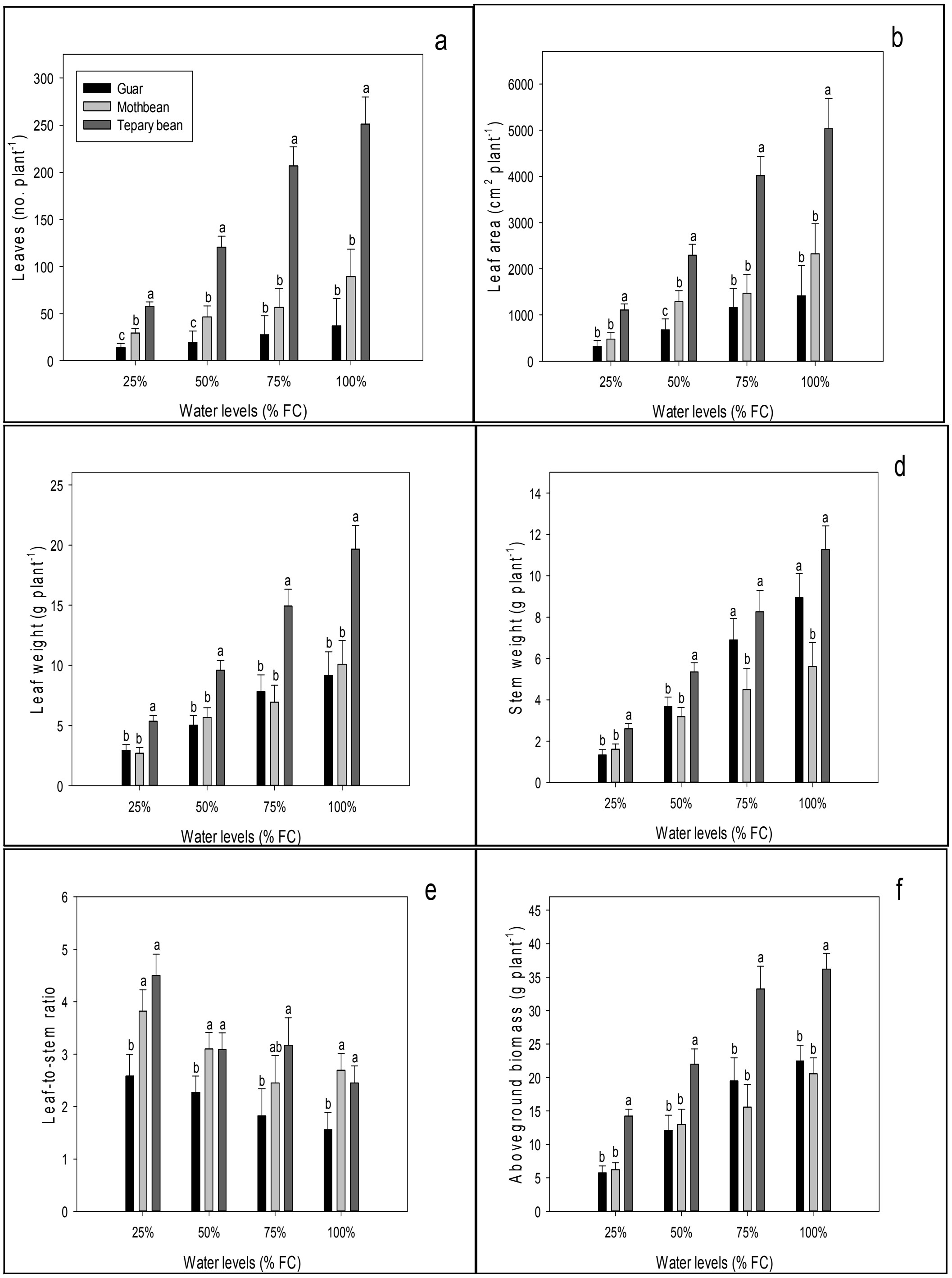

Figure 5.5. Effects of different water levels on (a) number of leaves, (b) leaf area, (c) leaf weight, (d) stem weight, (e) leaf-to-stem ratio, and (f) aboveground biomass of tepary bean (T), mothbean (M), and guar (G) at final harvest. Bars with same letters within a group of means are not significantly different according to least significant test at $p \leq 0.05$. Error bars are standard errors derived from one-way analysis of variance

CHAPTER VI

CONCLUSIONS

These research findings suggest that tested novel warm-season crops have some potential to aid in filling the forage deficit periods that generally occur during mid to late-summer period in the Southern Great Plains (SGP). Among three warm-season legumes, tepary bean emerged out as the most reliable forage option for the SGP due to its higher growth rates, water use efficiency and capability to generate consistently greater forage yields under different soil moisture levels. Higher leaf-to-stem ratios and digestibility of both tepary bean and moth beanforages indicated their superior forage quality compared to guar and other past tested legumes in the SGP. Additionally, both tepary bean and mothbean, due to their soil covering abilities, showed the potential of use as components of different strategies to increase precipitation use efficiency, minimize soil erosion, and meet nitrogen requirements for following crops. Although the forage yields of guar were considered adequate, a higher proportion of stems observed in biomass may limit its forage value compared to other potential legumes. Apart from legumes, finger millet possessed sufficient amounts of crude protein, lower fiber concentrations and higher digestibility than the traditional warm-season perennial grasses used to graze stocker cattle reported elsewhere, which indicates its potential for use in forage-livestock systems during summer in the SGP.

Future research efforts should be focused on defining management practices to enhance the production of these novel crops, and to test its function in more extensive production settings for grazing or hay production. Furthermore, systems-level water, nutrient, and economic impacts of growing these crops in rotation with winter wheat need to be evaluated for optimal enhancement and improved overall effectiveness of forage-stocker systems

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