Warm-season annual forage production systems in the semi-arid central Great Plains

by

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Abstract

The semi-arid Great Plains region has the highest concentration of beef cattle in North America, as well as a growing number of dairy cattle. This region, which stretches from the prairie provinces of Canada to the plains of Texas, is also experiencing declining aquifers for irrigation. This reduction in irrigation capacity creates the need for water-efficient forage-based cropping systems. Two studies were conducted in western Kansas to help improve the production of warm-season annual forages in the region. The first study evaluated the potential of summer annual legume species as more water-efficient alternatives to alfalfa, while retaining high forage nutritive value. This study sought to accomplish this by analyzing the viability, yield potential, nutritive value, water use efficiency, and economic returns of four summer annual legume species (cowpea [*Vigna unguiculata*], forage soybean [*Glycine max* (L.)], lablab [*Lablab purpureus*], and sunn hemp [*Crotalaria juncea*]) as well as two summer annual grass species (BMR forage sorghum [*Sorghum bicolor* (L.) Moench] and pearl millet [*Pennisetum glaucum*]). This study was conducted in 2022 and 2023 at three locations: Garden City, KS (irrigated), Colby, KS (dryland), and Hays, KS (dryland). Grasses were generally higher yielding and had greater water use-efficiency (WUE) than legume species. Lablab and cowpea were the only two legume species that had good establishment. Cowpea and forage soybean had significantly greater crude protein concentration ($\alpha = 0.05$) than either of the grass species, and cowpea, forage soybean, and lablab all had significantly greater relative feed quality (RFQ) values ($\alpha = 0.05$) than either of the grass species. Economic returns in irrigated environments were lablab = BMR forage sorghum = forage soybean = cowpea ≥ pearl millet ≥ sunn hemp ($\alpha = 0.05$), and in dryland environments were lablab = cowpea ≥ BMR forage sorghum ≥ pearl millet = forage soybean = sunn hemp ($\alpha = 0.05$). A second study analyzed the effect that seeding rate had on four summer

annual forage grasses: forage sorghum, sudangrass [Sorghum bicolor var. Sudanese], sorghum-sudan [Sorghum bicolor x S. bicolor var. Sudanese], and pearl millet. In 2022 and 2023, at Garden City, KS, and Hays, KS, four trials (two irrigated and two dryland) were conducted, where the above-listed species were planted at six different seeding rates, starting at 370,000 seeds ha^{-1} and increasing by increments of 370,000 seeds ha^{-1} to 2,220,000 seeds ha^{-1}. In 2024, at Garden City, KS, and Hays, KS, three additional trials (one irrigated and two dryland) were conducted for forage sorghum, which included seven seeding rates: 0.37 M, 0.74 M, 1.48 M, 2.22 M, 2.96 M, 3.7 M, and 4.44 M seeds ha^{-1}. Our results showed that seeding rate generally has a positive correlation with forage mass, with significant variation depending on the species and environment. We also established negative correlations between seeding rate and plant height, tillers per plant, stalk diameter, crude protein, and lignin concentration. Profitability varied greatly by species, seeding rate, and environment, with pearl millet consistently trailing the other three species due to generally lower yields. The findings of these studies will aid producers in the region as they integrate summer annual forages into their cropping systems by providing valuable information on the effects of crop choice and seeding rate on forage mass, forage quality, and profitability under both irrigated and dryland conditions.

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highest highs, and my rock in my lowest lows. You are the love of my life. I dedicate this work to you.

Chapter 1 - Introduction

Background and research justification

Much of agriculture in the semi-arid Great Plains revolves around the crop-livestock system. Crops such as alfalfa (Medicago sativa) are grown for forage, while corn (Zea mays) and sorghum (Sorghum bicolor) are grown to feed livestock as either grain or silage. These crops are good for meeting livestock protein and energy requirements. However, due to the semi-arid climate of the region, the high water use of corn and alfalfa makes their productivity highly dependent on irrigation from the Ogallala Aquifer (Steward et al., 2013; Klocke et al., 2013). After over 75 years of utilization for irrigation, the Ogallala Aquifer is in decline to the point that its ability to support irrigated agriculture is degraded, particularly in the southern and central Great Plains (Aistrup et al., 2017). In some regions, such as west-central Kansas (Greeley, Wichita, and Scott counties) many wells are already effectively exhausted (Buchanan et al., 2023). While in other areas with greater original aquifer saturated thickness, irrigation wells are expected to produce for decades to come but are seeing yearly declines. For the crop-livestock system of the semi-arid Great Plains to be sustainable, more water-use efficient cropping systems need to be developed to aid those producers that have already made the transition to dryland farming and to optimize the use of the irrigation resources that remain. Alternative forage crops to corn and alfalfa that are more water-efficient and drought-tolerant are critical for the region's cropping systems to become less dependent on irrigation from the Ogallala Aquifer.

The purpose of this research was twofold. First, six different potential warm-season annual forage species were evaluated for their water-use efficiency, forage mass, forage nutritive value, and profitability to assess their suitability for dryland semi-arid Great Plains cropping systems. The species evaluated included two grass species, brown midrib forage sorghum

(Sorghum bicolor (L.) Moench) and pearl millet (Pennisetum glaucum), as well as four legume species: cowpea (Vigna unguiculata), forage soybean (Glycine max L.), sunn hemp (Crotalaria juncea), and lablab (Lablab purpureus). Second, four species of warm-season annual forages, including forage sorghum, pearl millet, sudangrass (S. bicolor var. Sudanese), and a sorghum-sudangrass hybrid (Sorghum bicolor x S. bicolor var. sudanese), were planted at a range of seeding rates. We quantified the impact of seeding rate on forage mass, forage nutritive value, stalk diameter, tillering, stem-to-leaf ratio, and profitabilty. This information will provide production recommendations for these warm-season annual forages in the Great Plains. Furthermore, the information obtained through these studies will guide the transition to more water-efficient forage production systems in the semi-arid Great Plains, which will help maintain the continued prosperity of the crop-livestock production system while reducing dependence on irrigation.

Research Objectives

The objectives of this research were to:

1. Determine the forage mass potential, forage nutritive value, water-use efficiency, and profitability of six warm-season annual forage species (four legume species and two grass species).
2. Assess the impact of seeding rate on forage mass, stalk diameter, leaf-to-stem ratio, plant height, tillering potential, forage nutritive value, and profitability of summer annual forage grasses in both irrigated and dryland environments.

Research Hypotheses

The hypotheses for these objectives are as follows:

1. Grass species will produce more forage yield and better water productivity than legumes but will have lower crude protein and higher fiber content (Objective 1).
2. Annual legume species performance will vary, and certain species will be identified as potential alternative crops for the semi-arid Great Plains (Objective 1).
3. For summer annual forage grasses, higher seeding rates will result in smaller stalk diameters, greater leaf-to-stem ratios, and forage with lower fiber and greater crude protein concentrations (Objective 2).
4. For summer annual forage grasses, forage yields will be maximized at different seeding rates for different species in different environments (Objective 2).

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Chapter 2 - Literature review

Agroecology of the semi-arid Great Plains

The Great Plains is a semi-arid region that stretches north and south from the prairie provinces of Canada to the plains of Texas (Robinson & Nielsen, 2015). Geologist and explorer John Wesley Powell defined the 100th meridian west as its eastern edge, separating it from the wetter prairie region to its east, and the foothills of the Rocky Mountains as its western border (Krajick, 2020). Precipitation changes rapidly as you move west-to-east across the region, with an additional inch of annual rainfall for every 25 miles you travel to the east (Robinson & Nielsen, 2015). The far eastern edges of the region receive approximately 20 inches of rain per year, while the far western reaches receive as little as 12 inches per year (Opie, 2018, p.14). About 75% of the annual precipitation is received between April and September (Palecki et al., 2021).

Temperature is the primary variable from north to south in the region. The northern regions are generally colder, with longer winters and shorter summers, while the southern regions are hotter, with longer summers and shorter winters. The central regions serve as an intermediary between the two. Evaporation rates follow the same pattern as temperature, with the northern part of the region experiencing significantly lower evaporation rates than the southern part (Peterson & Westfall, 2004).

These two climatic factors, precipitation and temperature (along with their influence on evaporation rates), are the primary drivers of the cropping systems in the region. In the Great Plains, the evaporation potential exceeds precipitation most of the year (Peterson & Westfall, 2004). Outside of the sections of the region that are under irrigation, the entire region is under dryland conditions, which Robinson and Nielsen define as “regions where producing a crop on

growing season precipitation alone is not possible" (2015). This is opposed to rainfed conditions where "annual crop production is possible with solely growing season precipitation" (Robinson & Nielsen, 2015). These harsh and variable climatic conditions have given the region a unique agricultural history and a distinct set of cropping systems, which will be explored in the following sections.

A brief history of semi-arid Great Plains agriculture

The region was once a vast sea of short-grass prairie that supported large herds of bison for millennia, and then, for a brief couple of decades, the cattle drives of the legendary cowboy era. However, toward the end of the 19th century, homesteaders began to transform the region into vast swaths of agricultural monocultures, which still cover the landscape to this day. The age of agriculture on the semi-arid Great Plains can be divided into four distinct periods: The Great Plow-Up, The Dust Bowl, The Irrigation Revolution, and An Aquifer in Decline.

The Great Plow-Up: dryland framing pre-Dust Bowl

The pre-Dust Bowl era of Great Plains agriculture was an era of booms and busts driven by the region's sporadic precipitation patterns, which in good times resulted in years of bumper crops that could quickly spiral into years of drought and near-complete crop failure. The first boom cycle, which ran from 1878 to 1887, was driven by a "climate anomaly" of inordinate rainfall for the typically semi-arid Great Plains (Opie, 2018, p. 56). It was during this time that the catchy (and pseudoscientific) saying "rain follows the plow" gained traction, reflecting the belief of many farmers, U.S. government officials, and private land speculators that the region's climate had permanently changed for the wetter (Opie, 2018, p. 56).

However, the good times did not last. By 1888, a drought had begun. The entire decade of the 1890s brought only two good years of crops separated by five consecutive years of crop

failure. Between 1890 and 1900, the 24 counties of western Kansas experienced a decline from 14,300 to 8,900 farms (Opie, 2018, p. 59). It is worth noting that at this time, efforts were underway to stabilize the boom-bust cycle of Great Plains agriculture through irrigation, particularly in areas near the Cimarron and Arkansas rivers. One of the earliest projects, beginning in 1882, was the 96-mile man and horse-dug Soule Canal irrigation system between Cimarron and Spearville, KS (Kansas Historical Society, 2018). By 1924, farmers irrigated 20,000 acres by pumps and 80,000 acres by canals connected directly to the two rivers. However, Kansas State Irrigation Commissioner at the time, George S. Knapp, believed that this was the maximum limit for irrigation in the region because irrigation outside of the two river valleys was too expensive to support a profitable crop (Opie, 2018, p. 83). Early irrigation systems could only pump water from wells that were at most 20 feet deep because wind powered the pumps. After depleting the shallow water, irrigation wells required pumping water from depths of 300 to 500 feet, which necessitated the use of engines or motors technology that was either unavailable or too expensive for farmers in the late 19th and early 20th century.

However, these irrigated acres were a drop in the bucket compared to the millions of acres under dryland cultivation in the area. By 1910, the “golden age” of dryland agriculture in the region had begun. Uniquely favorable economic conditions, driven by high grain demand resulting from World War I and a subsequent famine in Europe, combined with relatively stable rainfall and agricultural mechanization, ushered in a boom period that lasted nearly two decades. In the last five years of the 1920s, Homesteaders plowed up 5.25 million acres, and wheat (Triticum) production grew by nearly 300 percent (Opie, 2018, p.88). However, this unchecked growth eventually led to a vast oversupply of wheat. This surplus, combined with the onset of the Great Depression in the early 1930s, led to a dramatic decline in wheat prices. In July 1931,

dryland wheat farmers in the region harvested the largest crop they had ever seen, but by this time, wheat prices had fallen to 25 cents a bushel, one-tenth of their price at the end of World War I. “In the middle of abundance, farmers were going broke” (Opie, 2018, p.90). By August of 1931, the region had fallen into a drought. The double blow of poor economic conditions and lack of moisture caused many farmers in the spring of 1932 to abandon their bare fields, setting the stage for the worst environmental disaster in American agricultural history.

The Dust Bowl

The horrors of the Dust Bowl are well-documented, so only a brief synopsis of its cataclysmic impacts on the region is presented here. Dust storms blanketed the central and southern Great Plains throughout the 1930s. In 1937, Dodge City, Kansas, had over 120 dust storms, its peak for the decade. In 1938, Garden City, Kansas, reached its peak with over 80 dust storms that year (Chepil et al., 1963). This level of dust storms was not atypical for the region, but representative of the area that was the heart of the Dust Bowl, including southwestern Kansas, the panhandles of Texas and Oklahoma, southeastern Colorado, and northeastern New Mexico (Bolles et al., 2019).

The toll of the storms affected every aspect of life, including agriculture, physical health, mental health, and societal well-being. Grain production plummeted. As one example, in Grant County, Kansas, in 1931, 196,000 acres were planted to wheat; the following year, only a meager 27,000 acres were planted (Opie, 2018, p. 92). Respiratory diseases, including “dust pneumonia”, were widespread, and both the suicide and murder rate increased as people grew increasingly desperate (Opie, 2018, pp. 91-92).

The conditions in the region were so dire that many in the Roosevelt administration believed it was time to permanently abandon agriculture in the region and restore the land to

native grasses. In 1934, the Taylor Grazing Act brought an end to a century and a half of selling off the public domain for family homesteads, and the National Resource Board was given funding to reclaim and retire 75,000,000 acres of former Great Plains farm ground. By 1935, the Resettlement Administration began moving people off the land (Opie, 2018, pp. 96, 99).

However, many Plains farmers and their families did not want to leave. When the program of reclamation, retirement, and resettlement ended in 1947, the government purchased only 11,300,000 acres, barely 15% of what had been initially planned (Opie, 2018, p. 100). The farmers that remained believed that even this worst of busts would eventually come to an end, and they were right. By the early 1940s, the combination of returning rains and surging economic demand from the Second World War brought the boom times back to the Plains. "Even in places where five or six inches of topsoil had been lost, the central plains produced in 1942 a record wheat harvest that surpassed the bumper crop of 1931… Farm income rose 165 percent in the war years 1939–45, while farm mortgage debt declined almost 20 percent" (Opie, 2018, p.103).

Like clockwork, the cycle of boom and bust continued. By the early 1950s, the rains had receded, and the dust storms had returned. "The Filthy Fifties" was a shorter drought than the Dust Bowl, but nonetheless still devastated the region. The drought and dust storms degraded nearly 21,000,000 acres of farmland, and hundreds of millions, possibly even billions, of dollars' worth of wheat crop failed (Opie, 2018, p. 107). The rains returned by the end of the decade, and when severe drought struck again in the 1970s, for the first time in a century of High Plains agriculture, it did not bring with it calamity. In the time between the Filthy Fifties and the droughts of the 1970s, a new era dawned for Great Plains agriculture. Due to new developments in irrigation technology, farmers could now tap into a seemingly endless reservoir of water. The

Ogallala Aquifer, the largest concentration of freshwater on the continent, served as the fuel for an irrigation revolution that swept across the Plains faster than a prairie fire. The century-long battle against the region's sporadic rainfall was finally won.

The Irrigation Revolution

The ingredients for the cost-effective tapping of the Ogallala Aquifer came together in the late 1930s and early 1940s. The internal combustion engine, turbine pumps, right-angle gear drives, rotary well drilling, and cheap, abundant fuel made large-scale irrigation possible across the Plains (Musick et al., 1988; Watson, 2020). In the Texas High Plains alone, the number of irrigation wells increased from 8,400 in 1948 to 42,200 in 1957 and to over 71,000 by 1977 (Opie, 2018, p. 134). Although the dust storms of the 1950s caused both environmental and agricultural damage, it is speculated that the reason it did not rise to the level of destruction that the Dust Bowl did is that irrigation had already started to take hold on the Plains as well as the introduction of conservation practices such as crop-fallow and leaving more residue on the soil surface (Peterson & Westfall, 2004). Since the “Filthy Fifties”, there have been significantly fewer dust storms in the region than there were in the 1930s or 1950s, even though there have been multiple periods of drought in the last 70 years (Musick et al., 1990). However, those that have occurred have resulted in significant soil erosion, traffic accidents, and loss of life, so preventing dust storms remains a priority for the region.

An exponential increase in yield potential accompanied the widespread adoption of irrigation in the region. Irrigation resulted in yields that were double to quadruple those of dryland agriculture (Howell, 2001). The explosion in grain yields and favorable conditions for confined livestock feeding pens attracted the animal-feeding industry to the region. Large numbers of cattle feedlots, industrial swine barns (concentrated in the panhandle of Oklahoma),

and industrial dairy facilities decided to move to the region because of an abundance of nearby feed supplies, dry conditions and limited surface water which reduced concerns over environmental pollution, and relatively lax regulations (the final reason playing a significant role in many dairies moving from California to the region) (Opie, 2018. pp. 147-178; Watson, 2020).

Once the animal feed industry moved into the region, beef and pork processing plants soon followed. In the 2010s, forty percent of American cattle were slaughtered within 250 miles of Garden City, Kansas (Opie, 2018, p. 149). Thus, the modern agricultural system for the region was established. Irrigation brought a permanent boom of grain crop yields as well as alfalfa (Medicago sativa) hay, corn (Zea mays), and sorghum (Sorghum bicolor (L.) Moench) silage. The large amount of available feed attracted feedlots and industrial swine and dairy barns, and the animal feeding industry attracted meat processors to the region. This vertical integration of agriculture has made the region an agricultural powerhouse. The first congressional district of Kansas, which encompasses all of western Kansas, ranks third in the nation for the market value of agricultural products sold (USDA-NASS, 2017).

An aquifer in decline: the future of irrigation on the semi-arid Great Plains

Mass irrigation from the Ogallala Aquifer transformed High Plains' agriculture both agronomically and economically. Between 1960 and 2007, irrigation increased yields by 51% for the region. Due to these yield gains, irrigation from the aquifer is worth $3 billion annually (García Suárez et al., 2019). This irrigation boom has had a particularly significant impact on the central and southern High Plains. In the southern High Plains, 72% of the region's total crop production value can be directly attributed to irrigated crop production (Terrell et al., 2002).

The Ogallala Aquifer is massive. It is the largest freshwater aquifer in the world and underlies 450,600 km² across eight states (Thelin & Heimes, 1987). However, it is not inexhaustible. While some regions that overlay the aquifer (primarily in the northern and eastern portions of the aquifer) can achieve sustainable levels of withdrawal due to higher recharge rates and lower evaporative demands, regions with low recharge rates and high evaporative demands, common in the southern High Plains and the western portions of the central and northern High Plains regions, have already seen significant losses in aquifer saturated thickness (McGuire, 2017; Scanlon et al., 2012).

Irrigated crop production using high-capacity irrigation wells is generally assumed to be uneconomical and impractical once an aquifer's saturated thickness drops below 30 feet due to low well yield (Rawling & Rinehart, 2018; Schloss et al., 2002). Studies have found that 24% of irrigated acreage may lose access to irrigation by 2100 due to the aquifer falling beneath the necessary level of saturated thickness to support adequate well yield (Deines et al., 2020). However, this loss of irrigation access is not spread equally across the aquifer. In the central High Plains, 40% of currently irrigated land is expected to lose access by 2100, while in the southern High Plains, this number is 54%. On the contrary, the northern High Plains, which generally has lower evapotranspiration (ET) rates and higher natural recharge compared to the rest of the High Plains, is projected to lose access to only 10% of its currently irrigated land (Deines et al., 2020).

The Texas Panhandle, southwest Kansas, eastern Colorado, and eastern New Mexico have already experienced a net reduction in irrigated acres between 1997 and 2017 (Hrozencik, 2023). Researchers expect this trend to continue. Consequently, many irrigated acres will eventually transition to dryland farming. Thus, there is a growing interest and need for

sustainable and profitable dryland cropping systems in the region. In addition to reduced irrigation capacity, irrigation water quality significantly decreases as the saturation thickness decreases. The remaining irrigation water is high in salts and uranium, often making it unusable for agricultural or domestic uses (Haskell et al., 2022; Hudak, 2005).

Dryland cropping systems of the semi-arid Great Plains

Now that we have established why irrigation is not a permanent solution for High Plains agriculture, we will explore the cropping systems that have the potential to succeed without irrigation in the region. These cropping systems do not preclude the use of irrigation, as some producers may choose to enhance the yield potential of these systems by utilizing their remaining irrigation resources. However, at the heart of each of these systems is the goal of remaining resilient, productive, and profitable without the use of irrigation. The four types of cropping systems that we will analyze are grain-based cropping systems, integrated grain and forage cropping systems, continuous forage-based cropping systems, and integrated crop-livestock systems.

Grain-based cropping systems

Wheat has long been the center of dryland grain-based cropping systems in the semi-arid Great Plains. Until the late 20th century, this often took the form of a wheat-fallow cropping system. Producers utilized fallow to reduce crop failure in the precipitation-limited environment (Peterson et al., 1996).

However, as no-till systems, herbicidal control of weeds, and wider accessibility of synthetic fertilizers began to maximize the precipitation use efficiency (PUE) of wheat-fallow systems, farmers sought out other cropping systems to improve the PUE of semi-arid High Plains cropping systems. Researchers and producers found that a three-year wheat-summer crop-fallow

rotation yielded higher annual grain yields, improved soil quality, and increased water use efficiency as compared to a two-year wheat-fallow rotation (Hanson et al., 2012; Tarkalson et al., 2006; Peterson & Westfall, 2004)—consequently, wheat-grain sorghum-fallow and wheat-corn-fallow have become the dominant grain-based cropping systems in the semi-arid Great Plains. Generally, in northern areas of the semi-arid Great Plains, wheat-corn-fallow has been the preferred system. Whereas, in the southern Great Plains, wheat-grain sorghum-fallow has taken preference. This is because grain sorghum is better suited to the higher ET and longer growing season of the southern High Plains. In contrast, corn can better tolerate the cooler early spring temperatures in further north areas (Peterson & Westfall, 2004).

In more recent years, researchers have studied the feasibility of replacing the fallow period in a wheat-summer crop-fallow cropping system with a cover crop. Results have been mixed to this point. In years with above-average precipitation, the inclusion of a cover crop reduced subsequent wheat yields by 0-34%, but in years with below-average precipitation, the inclusion of a cover crop reduced subsequent wheat yields by 40-70% (Holman et al., 2018). These results suggest that for cover crops to work effectively in place of fallow, some kind of flex-fallow system will be necessary, where the decision to plant a cover crop or extend the fallow period will be made year-to-year, depending on available soil water and precipitation outlooks. Multi-year studies have documented differences in wheat yields, precipitation use, and water storage efficiency based on the type of cover crop used and whether the cover crop was harvested for grain, cut for hay, or left standing (Holman et al., 2018; Holman et al., 2021). Replacing fallow with a cover crop reduced net returns by 50 to 100%. However, when a forage crop was grown in place of fallow, net returns increased by 26 to 240% (Holman et al., 2018). These results suggest that integrating annual forages into semi-arid Great Plains cropping

systems has the highest potential for adoption if further intensification of wheat-summer crop-fallow systems is desired.

Integrated Forage/Grain Systems and Continuous Forage Systems

There are two primary approaches to incorporating forage crops into semi-arid Great Plains cropping systems. First, there are integrated forage/grain systems that include both forage crops and grain crops in their crop rotation. Second, there are continuous forage systems, in which every crop in the rotation is a forage crop. Holman et al. (2022) explored several approaches to integrating forage crops into wheat-based grain cropping systems. Their integrated rotations included wheat -- forage sorghum -- fallow (W-FS-FL), wheat/double-crop forage sorghum -- grain sorghum -- forage oat (Avena sativa L.) (W/FS-GS-FO), wheat/double-crop forage sorghum -- forage sorghum -- forage oat (W/FS-FS-FO), wheat/double-crop forage sorghum-grain sorghum-fallow (W/FS-GS-FL), and wheat/double-crop forage sorghum-forage sorghum-fallow (W/FS-FS-FL). Grain sorghum yields decreased by 52-60% following wheat double-cropped with forage sorghum compared to the traditional W-GS-FL rotation (Holman et al., 2022). However, W/FS–FS–FO, the rotation with the greatest proportion of forages relative to grain, increased cropping intensity, productivity, resource use efficiency, and gross margin relative to other rotations in the semi-arid Great Plains (Holman et al., 2022). These results raise the question of whether it may be more beneficial to have rotations composed entirely of forages instead of trying to incorporate forage crops into existing grain-based cropping systems.

Nielsen et al. (2016) found that a continuously cropped all-forage rotation had a greater annual net income than either an integrated forage/grain rotation or an all-grain rotation. However, this study did not consider crop insurance paid when grain yield was near zero in some years, which might have resulted in different conclusions. This research confirms the value of

pursuing continuous forage systems for the semi-arid Great Plains. There are many different potential forage crops, including both cool-season and warm-season forage crops as well as grass species and legume species, so there are many different potential forage-based crop rotations. Over the past decade and a half, as there has been a growing awareness of the potential for forage-based cropping systems in the semi-arid Great Plains, much research has been conducted around the essential question of which forage-based cropping rotations are the most resilient, productive, and profitable.

Most existing research on forage-based rotations has centered around three crops that are well adapted to the region: spring oat, forage sorghum, and winter and spring triticale [×Triticosecale Wittm. ex A. Camus (Secale ×Triticum)]. Currently, it is a common practice in the region for producers to grow either continuous winter triticale or continuous forage sorghum (both are used for grazing, hay, or silage). However, continuous winter triticale often develops winter annual grass weed problems, and continuous forage sorghum produces lower quality forage than does triticale or oat, so it is necessary to pursue effective cropping rotations of these three forage crops to balance forage yield, quality, and weed management concerns (Holman et al., 2018).

Holman et al. (2021b) analyzed four potential forage-based crop rotations: forage sorghum -- forage sorghum (S-S), triticale double-crop forage sorghum -- forage sorghum -- oat (T/S-S-O), triticale double-crop forage sorghum -- forage sorghum -- forage sorghum -- oat (T/S-S-S-O), and triticale -- forage sorghum -- oat (T-S-O). The researchers selected these rotations based on the results of Holman et al. (2020), which found that double crop triticale and forage sorghum outyielded continuous forage sorghum or continuous winter triticale, and that winter triticale outyielded spring triticale. The key results of Holman et al. (2021b) included that

annualized forage yield was significantly greater in S-S and T/S-S-S-O than T/S-S-O or T-S-O, annualized water use was in the order T/S–S–S–O>T/S–S–O>T–S–O=S–S, precipitation storage efficiency showed no significant differences among cropping systems. Finally, T/S-S-S-O had the best yield stability.

However, forage yield and water use are not the only measures that matter when it comes to forage production. Because forage is used as feed for cattle and dairy cows, forage quality is essential to producers because the value of forage is highly dependent on its nutritive content. Holman et al. (2023) analyzing the same set of treatments as Holman et al. (2021) found that crude protein concentration was 23%-31% greater for triticale – sorghum -- oat (T-S-O) and triticale double-crop sorghum – sorghum – sorghum -- oat (T/S-S-O) compared with continuous sorghum (S-S). The S-S treatment tended to have greater acid detergent fiber and neutral detergent fiber, but exhibited lower in vitro true dry matter digestibility, calcium, and phosphorus concentrations. In contrast, T/S-S-S-O (reduced till) was among the top in terms of net return, nutritive value, and productivity (Holman et al., 2023).

Integrated Crop-Livestock Systems

To this point, we have focused exclusively on agricultural systems that incorporate only crops and not livestock. This is because, during the 20th century, crop and livestock production became increasingly separated as most farms became increasingly specialized (MacDonald et al., 2013). However, there is a growing interest in the region in reintegrating crop and livestock production systems, particularly in forage-based systems, to diversify and increase whole-farm economics (Krall & Schuman, 1996; Martens & Entz, 2011; Russelle et al., 2007). Grazing cattle directly on forage crops eliminates the need to bale, ensile, or transport the crop, and can result in nutrient recycling through animal manure (Cicek et al., 2014; Martens & Entz, 2011). The semi-

arid Great Plains may be uniquely situated to lead the integration of crop and livestock systems due to its proximity to native rangeland and the extensive livestock market infrastructure already in place in the region (Kelly et al., 2021). With the growth of forage-based cropping systems on the semi-arid Great Plains, integrating livestock into these systems is an exciting area of growth that can further enhance the resiliency and profitability of agricultural systems in the region.

Economic and political influences on semi-arid Great Plains cropping systems

Factors other than just agronomy influence cropping systems in the semi-arid Great Plains. Economic and political factors influence how producers decide to structure their cropping systems. The feedlot and dairy industries strongly influence which crops are economically in demand across the region, and policies on issues such as crop insurance and water use have at times influenced producers' crop choices.

One of the most significant driving economic forces on southern and central Great Plains cropping systems is the presence of feedlots and an increasing number of dairies in the region. The four states of Nebraska (19.8%), Texas (18.9%), Kansas (17.5%), and Colorado (7.1%) contain 63.3% of the nation's feedlots (Droulliard, 2018), and the dairy industry is experiencing rapid growth in the region. In the Texas High Plains alone, dairy cow inventory grew from 12,066 to 262,622 head from 2000 to 2015 (Federal Milk Marketing Order 126, 2017). One of the main reasons the feedlot and confined dairy industry moved to the region was access to silage, cereal grains, grain byproducts, and low-cost feedstuffs. Thus, meeting the demand of these industries is one of the driving forces behind the cropping systems of the semi-arid Great Plains (Droulliard, 2018; Guerrero et al., 2012).

One of the primary policy factors shaping the region's cropping systems is crop insurance. Crop insurance can influence crop choice. Crops that are well-covered under crop

insurance become a less risky option for farmers than crops that are less well-covered or not covered at all (Goodwin & Smith, 2003; Walters et al., 2012). One example of this is in the Corn Belt, comprising Ohio, Indiana, Illinois, Iowa, and Missouri, where crop insurance has led to a 1.7% increase in corn acreage and an 8% decrease in wheat acreage (Claasen et al., 2017).

This is relevant to the semi-arid Great Plains because until 2014, annual forages were not covered under crop insurance (Ifft et al., 2023). However, there is evidence that the availability of annual forage insurance may benefit the region's forage growers. In Kansas, the number of square km enrolled in annual forage crop insurance increased from 380 in 2020 to 1,137 in 2023, with the majority of those acres concentrated in the western part of the state (Ifft et al., 2023; Ifft et al., 2022).

Water policy is another significant factor influencing the region’s cropping systems. Historically, water policy often provided perverse incentives that encouraged farmers to use irrigation in ways that did not maximize the efficient use of the Ogallala Aquifer. Previously, in Kansas, due to state laws, farmers could lose a portion of their ground and surface water rights if they did not use their full allotment each year. This policy led producers to use their full allotment, even in years when it did not necessarily benefit crop yields (Peck, 2003). However, in states such as Nebraska, Kansas, and Texas, groundwater management decisions have shifted to the local level in the form of groundwater management areas (GMA) that have the power to restrict groundwater use (Smidt, 2016). There are two different approaches these GMAs can take regarding their use of groundwater resources. The first approach is that of crafting policy in a way that intends “to extend the current agricultural production regime as long as possible” (Aistrup et al., 2017). This approach would allow communities to accumulate as many resources as possible before the current irrigation-based regime becomes unfeasible. The second approach

would be to utilize policy to expedite the transition toward a dryland-based agricultural production regime, as this is the ultimate destination for large swaths of the region (Aistrup et al., 2017). Which approach individual GMAs decide to take will have a significant influence on how farmers structure their cropping systems within a GMA.

Forage nutritive value

We have discussed why annual forages fit well into semi-arid Great Plains cropping systems due to their agronomic productivity, as well as their ability to meet the demands of the region's driving economic forces: feedlots and dairies. Before examining annual forage crops in more detail, it is necessary to address the topic of forage nutritive value. Yield is the primary objective in the agronomics of grain crops. However, in forage crops, both yield and forage nutritive value are critical components to the agronomy of forage crops. Forage nutritive value has a significant influence on realized livestock gains for a given amount of forage (Newman et al., 2007). This is why when evaluating forages, yield alone is not enough. It not only matters how much forage a producer can grow, but also what impact that forage has on animal performance. Forage yield and nutritive value are generally inversely related, so it is often important to find a balance between the two (Cusicanqui & Lauer, 1999; Huang et al., 2020; Liebert et al., 2023).

Multiple measures are available to evaluate forage nutritive value, including concentrations of crude protein, fiber, digestibility, and energy, as well as forage quality indices calculated using multiple individual measures. These measures can be expressed either as "as fed" (moisture included) or as "dry matter" (moisture excluded) (Van Saun, 2023). Dry matter percentage itself can be an important measure for forage growers because it should not exceed 15% in crops used for hay to prevent mold growth.

While sometimes used interchangeably with the term "forage quality", Newman et al. (2007) defined forage nutritive value as the "concentration of available energy and available crude protein." In contrast, forage quality is "a broader term that not only includes nutritive value, but also forage intake."

Crude protein

Crude protein (CP) is measured by taking the total nitrogen content (as measured by the Kjeldahl digestion method) multiplied by 6.25 (Lee, 2018). Protein supplementation is the most expensive component in livestock feeding programs; therefore, forage crops with high crude protein content are highly desirable (Lemus, 2020). Crude protein can vary widely based on forage species, nitrogen fertility, and forage maturity. Generally, legumes are between 12%-25% CP, cool-season grasses are between 8%-23% CP, and warm-season grasses are between 5%-18% CP (Adesogan et al., 2017). Crude protein content has a positive relationship with nitrogen fertilization levels (Ayub et al., 2009; Cinar et al., 2020; Holman et al., 2019; Johnson et al., 2001; Sebetha et al., 2015). Finally, as forages mature, crude protein content is diluted by increasing fiber, resulting in reduced nutritive value (Van Saun, 2023).

Fiber measures

Fiber content is the best single predictor of feed intake and digestibility; therefore, fiber measures are also important for determining forage nutritive value (Lee, 2018). The two primary fiber measures are acid detergent fiber (ADF) and neutral detergent fiber (NDF). Acid detergent fiber represents the plant's structural components (lignin, cellulose, silica, and insoluble nitrogenous compounds, but not hemicellulose). It is determined by weighing what remains after boiling in acid detergent. Neutral detergent fiber is what remains after boiling in neutral detergent and includes lignin, silica, cellulose, and hemicellulose. As ADF percentage increases,

digestibility will generally decrease, and as NDF percentage increases, total dry matter intake will generally decrease (Benedict, 2012). Consequently, high-quality forages will have both lower ADF and NDF values. For grasses and legumes, ideal ADF fractions are less than 35% (Van Saun, 2023). Regarding NDF, for grasses, an NDF fraction below 50% is considered high-quality forage, and an NDF fraction above 60% is considered low-quality forage. For legumes, an NDF fraction below 40% is considered good, and above 50% is considered poor.

Occasionally, lignin content is measured independently because it can have a significant impact on forage quality. Sometimes referred to as the "woody part" of a plant, lignin is the primary factor influencing cell wall digestibility (Benedict, 2012). As lignin increases, digestibility, intake, and animal performance all decrease. Lignin content is primarily based on species and maturity (Kondo et al., 1987). As plants mature, their lignin content increases; in general, woody species, such as trees and shrubs, contain higher levels of lignin than grass species and legumes.

Digestibility measures

There are three primary methods for measuring the digestibility of a forage: *in vitro, in situ,* and *in vivo. In vitro* means using test tubes with rumen fluid to test plant material digestibility (DePeters & Heguy, 2012). *In situ* means using animals with fistulas to test the digestibility of plant material. Both the *in vitro* and *in situ* methods expose forage samples to rumen microorganisms for a set period to determine what proportion of the sample the microorganisms digest. *In vivo* means directly feeding plant material to a live animal and estimating the amount that was digested by using some kind of tracer to measure the amount of that tracer that is found in the animal's excrement (Varga, 2023).

Both dry matter digestibility, which accounts for all nutrients, and organic matter digestibility, which includes all nutrients except ash, can be measured using all three of the techniques mentioned above (Lee, 2018). Sometimes, the digestibility of the NDF fraction is analyzed because the nutritional availability of NDF is not uniform throughout all forages (Adesogan et al., 2017). Neutral detergent fiber digestibility (NDFd) helps determine the energy value of a forage (DePeters & Heguy, 2012). All three methods for measuring digestibility can also be used to measure NDFd (DePeters & Heguy, 2012; Varga, 2023).

Energy measures

There are many different measures to quantify the total energy value of a forage. Total digestible nutrients (TDN) has been used for many years and is one of the most easily understood and widely recognized forage nutritive values (Adesogan et al., 2017). It is calculated as the sum of digestible protein, digestible crude fiber, digestible nitrogen-free extract, and 2.25 times the digestible fat concentration. Higher TDN values indicate a higher quality forage, and TDN decreases as a plant matures.

Net energy is another measure of the energy content of a forage. Conceptually, net energy is the portion of the ingested energy that is useful to the animal. It is measured in Mcal of energy per pound of forage (Rocateli & Zhang, 2017b). Practically, it is what remains after losses, such as energy in feces, urine, gas, and the work of digestion, are accounted for. There are three different net energy measures, depending on the productive purpose of the feed: net energy maintenance (NEm), net energy gain (NEg), and net energy lactation (NEl). Net energy-maintenance is an estimate of the energy value of a forage when used for maintaining an animal in a non-productive stage (not losing or gaining weight, producing milk, nor doing work on its environment); NEg is an estimate of the energy value of a forage for gaining weight once

maintenance is achieved; NEl is an estimate of the energy value of a forage for milk production during lactation. Net energy values are calculated from TDN values, and NEm and NEg are used for balancing rations for growing cattle, while NEl is used for balancing rations for dairy cows.

The last two energy measures are nonfibrous carbohydrate fraction (NFC) and nonstructural carbohydrate fraction (NSC). NFC is a measure of sugars, starches, and soluble fibers, while NSC is a measure of starch and sugar only (Van Saun, 2023). Higher values for NFC and NSC are indicators of high-quality forage.

Forage quality indices

Because there are many different measures of forage nutritive value, there have been a handful of efforts to index the various measures into a single value. The two most common indices are relative feed value (RFV) and relative forage quality (RFQ).

RFV is the older of these two indices and uses NDF and ADF as predictors of forage quality (Adesogan et al., 2017). RFV ranks the quality of a cool-season forage relative to alfalfa at full bloom. The RFV of alfalfa at full bloom equals 100, so RFVs greater than 100 would be considered a higher quality forage than alfalfa at full bloom, and RFVs less than 100 would be a lower quality forage than alfalfa at full bloom. Because alfalfa is a temperate cool-season forage, RFV should be used only to evaluate other temperate cool-season forage species.

RFQ is a newer index designed to apply to all forages (cool-season, warm-season, and tropical) except corn silage (Adesogan et al., 2017). It has the same mean and range as RFV, so it can be substituted for RFV when necessary. However, RFQ is based on CP, NDF, ADF, fat, ash, and NDFd, so comparing RFQ scores with RFV scores should be avoided whenever possible.

One final example of a forage quality index is milk per ton, which was developed by Undersander et al. (1993) and estimates lbs. of milk produced per ton of forage dry matter. The

index is based on ADF and NDF. Undersander et al. (1993) also created the measure of milk per acre, which is simply milk per ton multiplied by forage yield. The purpose of the milk per acre value is to capture a forage's yield and forage nutritive value in a single measure.

Cool-season vs. warm-season annual forages

Although both cool-season and warm-season annual forages can play roles in semi-arid Great Plains cropping systems, there are some key differences between the two. The four major annual forage crops in the region are forage sorghum, corn silage, oat, and triticale (Holman et al., 2023). Forage sorghum is well-adapted to the region due to its drought and heat tolerance (Bhattarai et al., 2019). Corn is the most abundant silage crop in the United States (Bhattarai et al., 2019). Valued for its high grain content, its silage is a high-energy and easily digestible form of forage. However, it uses more water than forage sorghum, and decreasing groundwater for irrigation, rising irrigation cost, and excessive summer dryness threaten corn production's sustainability on the High Plains, particularly the further south you move in the region. Triticale is well-adapted due to its winter hardiness and high regrowth potential, which makes it preferable to wheat for cool-season forage (Ayalew et al., 2018; Holman et al., 2010). Oat is also a cool-season forage, but it is less winter hardy, which is why it is often grown as a spring oat (Holman et al., 2020b). Oats' popularity is primarily due to their high nutritional value and preference among animals (Ayalew et al., 2019; Kim et al., 2014). In general, cool-season grass forage is higher in forage nutritive value while warm-season grass forage has greater biomass productivity (Lee, 2018; Lemus, 2020). For this reason, cool-season and warm-season forages are highly complementary in cropping systems (Holman et al., 2023). Although both cool-season and warm-season annual forages are important for semi-arid Great Plains agriculture, there are

more gaps in research surrounding warm-season annual forages in the region, so that they will serve as the primary focus of this thesis.

Warm-season annual forages

Warm-season annual forage is a broad category of crops that includes many different species, falling into two overarching groups: grasses and legumes. We will now examine some individual species of each, as well as the significant differences between warm-season annual grass and legume forage. This section will also contain information on mold damage and heat damage, which are potential issues for warm-season annual forage hay and silage. Warm-season annual forage water use will also be discussed in this section because water use is a significant consideration for all crops in this water-limited region.

Warm-season annual grass species

Four of the main warm-season annual grass species grown in the region for hay are forage sorghum, sudangrass (*S. bicolor var. Sudanese*), sorghum-sudangrass hybrids (*Sorghum bicolor x S. bicolor var. sudanese*), and pearl millet (*Pennisetum glaucum*) (Roozeboom et al., 2008).

Forage sorghum originated in the heart of Africa (modern-day Ethiopia and Sudan) (Bhattarai et al., 2019). Due to its origin in a semi-arid climate, it is a heat- and drought-tolerant crop that is well-adapted to semi-arid regions worldwide. It is a morphologically diverse species that includes many varieties. Forage sorghum will grow in soils of moderate fertility and grows best in soils of pH 6-7. It is not particularly tolerant of acidic or calcareous soils but performs better on heavier and wetter soils than pearl millet (Hanna & Sollenberger, 2007). Forage sorghum generally grows between 2 and 4 m tall (Bhattarai et al., 2019). It uses significantly less fertilizer and water than corn but is highly responsive to N fertilization (Newman et al., 2013;

Holman et al., 2019). However, sorghum silage is less energy-dense than corn silage (Bhattarai et al., 2019). In 2022, Texas (2.6 million tons on 175,000 acres) and Kansas (788,000 tons on 105,000 acres) were the highest sorghum silage-producing states (USDA-NASS, 2023). A study in the Texas High Plains found that if 30,000 acres currently in irrigated corn silage, irrigated grain sorghum, and dryland grain sorghum production were converted into irrigated forage sorghum silage production, the region's economy would see a $4.9 million benefit and would save 113,500 ac-ft of irrigated water (Almas et al., 2015). The most significant factor preventing this switch from taking place is the difference in forage nutritive value between sorghum and corn silage. Therefore, further improvements in brown midrib (BMR) forage sorghum genetics may be the key to facilitating this switch.

Sudangrass is technically a subspecies of sorghum, but producers often treat it as a distinct species due to its different growth habits and panicle structure (Bhattarai et al., 2019). Sudangrass tillers more than forage sorghum, has thinner stalks and narrower leaf blades, and can regrow more rapidly (Pedersen & Rooney, 2004). Sudangrass is primarily used for grazing and hay (Pedersen & Rooney, 2004; Roozeboom et al., 2008).

Sudangrass readily hybridizes with forage sorghum to create sorghum-sudan (Bhattarai et al., 2019). These hybrids act as an intermediary between the two, with the tall, thick stalks of forage sorghum and the leafiness and tillering potential of sudangrass. Sorghum-sudan can be used for silage or hay (Pedersen & Rooney, 2004). Sorghum-sudans also work very well as a cover crop due to their ability to quickly add organic matter to worn-out soils, as well as suppress weeds and nematodes (Sustainable Agriculture Research and Education, 2007).

Pearl millet is a morphologically diverse species that originated in northern Africa. It can grow up to 5 m tall, but most cultivars typically reach a height of 2-3 m (Hanna & Sollenberger,

2007). Pearl millet is well suited to the semi-arid Great Plains because it thrives between 77-95 ºF (Marsalis, 2012). However, it is sensitive to cold early in the growing season (Marsalis, 2012). Pearl millet is also known for its productivity even in soils with low nutrient and moisture content, as well as its higher tillering potential and leafiness (Kumar, 1989; Singh et al., 2017; Marsalis, 2012). It grows best on well-drained loamy or sandy soils (Hanna & Sollenberger, 2007).

Two things to be conscious of in warm-season annual forage grasses are prussic acid poisoning and nitrate poisoning. Members of the sorghum family contain dhurrin. The metabolism of dhurrin by ruminants can lead to the release of hydrogen cyanide, a deadly toxin also known as prussic acid, into the animal (Gleadow & Møller, 2014). Dhurrin concentration is highest in forage sorghum in young growth or regrowth (Halkier & Moller, 1989; Burke et al., 2013). As the plant ages, dhurrin concentration declines but can increase again due to drought, over-fertilization, and frost (Harms & Tucker, 1973; Wheeler et al., 1990; Busk & Moller, 2002; O'Donnell et al., 2013; Gleadow & Møller, 2014; Neilson et al., 2015; Tuinstra et al., 2022; Gruss et al., 2023). The potential for prussic acid poisoning is not reduced by haying; however, ensiling can reduce prussic acid by up to 80% (Stuart, 2012). Sudangrass has 1/3 of the dhurrin content of forage sorghum, and sorghum-sudan falls between the two (Menual & Dowell, 1920). One significant advantage of pearl millet is that it does not pose concerns for prussic acid poisoning (Bhattarai et al., 2019). Breeders are releasing lines of sorghum with little to no dhurrin, which may have a significant impact on the future of prussic acid concerns in sorghum (Tuinstra et al., 2016)

One toxicity concern that all the aforementioned summer annual forages share is nitrate toxicity. Environmental stresses, such as drought, frost, and/or cloudy weather, combined

with high manure or N fertilizer rates, can cause forage crops to accumulate greater levels of nitrates in their above-ground biomass (Maryland et al., 2007). High nitrate levels in the rumen convert to nitrite; this nitrite then enters the blood and blocks the transport of oxygen by red blood cells, resulting in asphyxiation (Kemp et al., 1977). Forage containing less than 3,000 mg kg^{-1} nitrates is considered safe for feed; forage containing between 3,000 mg kg^{-1} and 6,000 mg kg^{-1} nitrates can be fed if mixed, and forage above 9,000 mg kg^{-1} should not be fed at all (Roozeboom et al., 2011). Holman et al. (2019) found that N application rates greater than 70 kg N ha^{-1} are likely to produce forage above the safe level of 3,000 mg kg^{-1} nitrates. Haying does not reduce nitrate levels, but ensiling can reduce nitrates by 40-60% in pearl millet and by 30-50% in sorghum (Sheahan, 2014; Strickland et al., 2013). Increasing cutting height can also reduce nitrate in feed because nitrate concentrations are greatest in the stalk base and lowest in the head and leaves (Roozeboom et al., 2011; McCreery et al., 1966; Burger & Hittle, 1967). In a study on drought and heat stress, sudangrass and sorghum-sudan had lower nitrate levels than pearl millet (Strickland et al., 2013). However, a study based on survey results from Kansas and Nebraska farmers, as well as an analysis of forage samples submitted to a commercial testing laboratory in Nebraska, found no significant difference in the likelihood of nitrate toxicity between millets and forage sorghums or sudangrasses (Lenz et al., 2019).

Warm-season annual legume species

Many different warm-season annual legumes can be grown as forage. However, a few that are of interest in the region are cowpea (Vigna unguiculata), forage soybean (Glycine max), sunn hemp (Crotalaria juncea), and lablab (Lablab purpureus). Cowpea is a drought-tolerant legume species that originated in sub-Saharan Africa and is used both as a vegetable crop for humans and forage for livestock (Boukar et al., 2019; Smith et al., 2020). Forage cowpeas are

widely used in Texas and the southeastern United States as wildlife food for white-tailed deer (Smith et al., 2020). In Africa, cowpea is primarily grown in dry savannahs and Sahel regions that receive less than 300 mm of rain a year (Boukar et al., 2019). Cowpea's drought tolerance makes it an excellent potential fit in Great Plains dryland cropping systems. Along with its drought tolerance, cowpea is also an ideal forage because it has a high nutritive value and does not cause bloat in ruminants (Caddel & Enis, 2017).

Forage soybeans are the same species as grain soybeans, but they have been bred for forage potential instead of grain yield. They are typically used for short-season grazing or hay, but unlike many other forages, they do not regrow after defoliation (Sollenberger & Collins, 2003). Yields increase with maturity until 75%-90% pod fill, after which leaf loss decreases yield and forage quality. Soybean hay is difficult to cure and particularly susceptible to mold (Sollenberger & Collins, 2003).

Sunn hemp is a tall annual legume originating on the Indian subcontinent (Mosjidis et al., 2012). In India, the plant is typically used for its fiber and occasionally as hay; however, it was introduced to the U.S. in 1899 due to its ability to grow in low-fertility soils, its nematode resistance, and its capacity to increase soil organic matter and soil quality (Mosjidis et al., 2012). Interest in sunn hemp has increased in the U.S. recently over its potential to serve as a summer cover crop and green manure (Mosjidis et al., 2012). In the 20th century, concerns arose that sunn hemp forage might be toxic; however, further research has since shown that it is not. However, sunn hemp seeds in large doses can be toxic to livestock (Mosjidis et al., 2012). Historically, due to its long growing season requirement, sunn hemp did not produce seeds in the temperate climates of North America, and seeds were shipped to North America from South America (Mosjidis et al., 2012). However, a team of researchers at Auburn University developed

cultivars in the early 21st century that produce seeds in the temperate climates of North America (Mosjidis et al., 2012). This has increased interest in the crop because it has made breeding and seed production feasible within the United States, thus increasing the availability of the crop.

Lablab is a highly variable species of forage legume with 20-50 botanical varieties (Pittman & Kretschmer, 2007). It is drought-tolerant and grows well in slightly acidic to alkaline soils (Pittman & Kretschmer, 2007). Producers have grown it for both grazing and human consumption worldwide. It is typically strip-grazed, with cattle eating only the leaves and then quickly removed to allow for regrowth. In the U.S., it has primarily been used in wildlife food plots.

Mold damage and heat damage in warm-season annual forages

Mold damage is a concern in both hay and silage. Mold damage can reduce the quality of forage and cause health problems in animals that consume the feed (Amigot et al., 2006). Mold toxicity is generally a bigger threat to horses than ruminants (Jacobsen, 2016). However, even in ruminants, mold contamination in silage can cause respiratory problems, abnormal ruminal fermentation, diminished reproductive function, reduced production, renal damage, skin and eye irritation, and moldy hay can cause mycotic abortion and aspergillosis (Scudamore & Livesey, 1998; Gotlieb, 2002; Lacey et al., 1978). The presence of molds can also reduce palatability, leading to a decrease in forage intake (Adesogan et al., 2002). When forage is harvested at improper moisture levels, damaged by rain, or stored improperly, microorganisms can break down crude protein into peptides, amino acids, amines, and ammonia; this significantly reduces the forage protein fraction, resulting in an overall degradation of forage nutritive value (Adesogan et al., 2002; Driehuis & Elferink, 2000).

Heat damage to hay is also a concern. Excessive heat in hay can cause the protein to denature, reducing crude protein content (Ramsdale, 1995). This is especially a problem in legume hay, such as alfalfa. Heat damage is primarily a concern after baling (Anderson, 2009). The primary cause of heat damage in baled hay is baling when the hay is too moist. For small square bales, hay should be baled between 15-22% moisture, while large round bales should not be baled if moisture is above 18% (Dorward, 2018). The primary source of heat in hay is the metabolic activity of microorganisms (Anderson, 2009). Microbial activity increases as hay moisture increases. Hay with only a little excess moisture will generally not reach a temperature higher than 49ºC, a temperature that is generally considered safe. However, wetter hay can quickly rise to 66ºC. At this temperature and higher, hay will nearly always become discolored and lose nutritional value. If the hay temperature rises above 77 °C, a chain of chemical reactions can quickly raise the hay temperature to over 205 °C and start a fire.

Warm-season annual forage water use

Forage crops have a higher water use efficiency (WUE) than grain or seed crops because forages typically produce only vegetative biomass. In contrast, grain crops must grow vegetative biomass plus grain (Nielsen et al., 2006). Corn silage is a preferred forage choice because it has a high proportion of grain, making it high in energy and easily digestible. However, dryland corn production is risky in the semi-arid Great Plains because corn has a high water use requirement and low drought tolerance (Bhattarai et al., 2019; Steward et al., 2013). In a study analyzing silage yield on the Texas High Plains, Bhattarai et al. (2020) found the following ranking for WUE of warm-season annual forages: forage sorghum > pearl millet > corn. Corn grown for forage uses 27-31 in. of water throughout a season in the Texas High Plains, while forage sorghum uses only 21-26 in. of water (Enciso et al., 2004). In general, warm-season forage

crops have a higher WUE than cool-season forage crops, and annual forages have a higher WUE than perennial forages (Gelley et al., 2020).

Warm-season annual forage management

Warm-season annual forage production involves numerous management decisions that can have a significant impact on forage yield and quality. Some of these decisions include seeding rate, planting depth, row spacing, planting date, maturity at harvest, fertility, pest control, and tillage operation.

Seeding rate and planting depth

Studies on warm-season annual forage grasses produced mixed results on whether seeding rate had a significant effect on forage yield. Snider et al. (2012) found that in three of four site-years, sorghum biomass yield was not significantly affected by seeding rate, but in one site year, a seeding rate of 116,000 seeds ha^{-1} outyielded a seeding rate of 393,000 seeds ha^{-1}. Mekasha et al. (2022) found that the seeding rate significantly impacted dry matter accumulation in sorghum in a study that included seeding rates of 12.5, 25, 50, 75, and 100 kg ha^{-1}. In a study that included plant populations of 80,000, 100,000, 120,000, and 140,000 plants ha^{-1} and row spacings of 50, 70, 90, and 110 cm, May et al. (2016) found that row spacing significantly influenced the fresh biomass yield of sorghum more than the plant population density. This result was because losses in plant population were compensated by tillering, which was greatest in the narrowest row spacing (May et al., 2016). In a study comparing seeding rates of 200,000 seeds ha^{-1} and 300,000 seeds ha^{-1} for brachytic dwarf BMR forage sorghum, Elango et al. (2020) found no significant difference between seeding rates in terms of dry matter yield. In a study with four seeding rates of pearl millet (5, 10, 15, and 20 kg ha^{-1}), Bouchard et al. (2011) did not find a significant effect of seeding rate on biomass yield.

When it comes to forage quality, Mekasha et al. (2022) found that increasing the seeding rate significantly decreased NDF, ADF, and acid detergent lignin, while leading to an increase in in vitro organic matter digestibility, resulting in an overall improvement in forage quality. However, the seeding rate did not significantly impact CP (Mekasha et al., 2022). Elango et al. (2020) found no significant difference in CP fraction, starch content, NDFD, or net energy lactation between brachytic dwarf BMR forage sorghum seeded at 200,000 seeds ha^{-1} and 300,000 seeds ha^{-1}.

Results are varied for biophysical traits such as plant height, tillers, and stalk diameter. Mekasha et al. (2022) and Snider et al. (2012) found that seeding rate had different impacts on plant height at various locations. Some test sites revealed a significant positive relationship between plant height and seeding rate, while others showed an inverse relationship between the two. In a study on the impacts of seeding rate in pearl millet, Bouchard et al. (2011) found a significant inverse relationship between seeding rate and number of tillers. Mekasha et al. (2022) found a significant inverse relationship between stalk diameter and seeding rate at all three locations of their study. This is an important finding because Pigden and Heinrichs (1957) found that finer stems may contain lower lignin contents, which could improve digestibility. Additionally, large stems have a higher crude fiber content than thin stems (Mowat et al., 1966).

Current K-State Extension publications recommend a seeding rate of 11-22 kg ha^{-1} for forage sorghum on narrow rows (typically used for hay and grazing) and 4-7 kg ha^{-1} on wide rows (typically used for silage) (Roozeboom et al., 2008). For sudangrass and sorghum-sudan in narrow rows, a rate of 11-17 kg ha^{-1} is recommended for dryland production in western Kansas and 34 kg ha^{-1} for irrigated production. For pearl millet, the dryland recommendation for western

Kansas on narrow rows is 6-17 kg ha^{-1}, and the irrigated recommendation is 11-22 kg ha^{-1}. The recommended planting depth for forage sorghum, sudangrass, and sorghum-sudan is 2.5 to 3.8 cm, but for pearl millet, it is 1.9 to 2.5 cm because pearl millet has a much smaller seed.

For comparison, Texas A&M AgriLife Extension recommends a seeding rate of 17-22 kg ha^{-1} drilled and 22-28 kg ha^{-1} broadcast for forage sorghum and sorghum-sudan, 22-28 kg ha^{-1} drilled and 34-45 kg ha^{-1} broadcast for sudangrass, and 11-17 kg ha^{-1} drilled and 28-34 kg ha^{-1} broadcast for pearl millet (Corriher, 2013). To the north, the University of Nebraska-Lincoln recommends a seeding rate of 11 kg ha^{-1} for forage sorghum, 22 kg ha^{-1} for pearl millet and sudangrass, and 28 kg ha^{-1} for sorghum-sudan (Drewnoski & Redfearn, 2017). They also recommend a planting depth of 2.5 cm for forage sorghum, sudangrass, and sorghum-sudan and 1.25 cm for pearl millet. To the east, the University of Missouri-Columbia Extension recommends a seeding rate of 22-28 kg ha^{-1} for drilled sorghum-sudan and 34-39 kg ha^{-1} for broadcast, as well as a seeding rate of 17 kg ha^{-1} for drilled pearl millet and 22-34 kg ha^{-1} for broadcast-seeded pearl millet (Kallenbach et al., 2001). They also recommend a planting depth of 1.25-2.5 cm for sorghum-sudan and 1.9-2.5 cm for pearl millet. To the south, Oklahoma State Extension recommends a seeding rate of 45-112 kg ha^{-1} for cowpea (Caddel & Enis, 2017).

Row spacing

Forages grown for silage are often planted with row-crop planters using 50 or 75-cm row spacing for ease of harvest with silage equipment (Undersander, 2014; Bean & Marsalis, 2010). Forages grown for hay or grazing are most commonly drilled using a 19- to 30-cm row spacing, but can also be broadcast-seeded. Forage sorghum can be grown for silage or hay, but producers normally plant sudangrass, sorghum-sudan, and millet for hay, so they are drilled using narrower row spacing. Snider et al. (2011) found that biomass production for photoperiod-sensitive

sorghum was highest in 19 cm rows compared to 38 cm rows or 76 cm rows in non-water-limited environments in Arkansas and Alabama. May et al. (2016) similarly found that fresh biomass for sorghum was highest in the narrowest rows tested in a study conducted in the central region of the Brazilian state of Minas Gerais. Treatments in this study included row widths of 50 cm, 70 cm, 90 cm, and 110 cm. In a study in western Oklahoma analyzing the impact of row spacing on three forage legumes (forage soybean, tepary bean [Phaseolus acutifolius], and moth bean [Vigna aconitifolia]), narrow row spacing (38 cm) resulted in more forage production than wide rows (76 cm) (Baath et al., 2014).

Planting date recommendations

In a study in eastern New Mexico, forage sorghums planted in late May or early June outyielded those planted in late June or July (Lauriault et al., 2012). Current K-State Extension recommendations are to plant forage sorghum between May 15th and June 20th, to plant sudangrass and sorghum-sudan between May 20th and July 10th, but to wait until between June 1st and July 1st for any millet crop because they cannot tolerate cold, wet soils (Roozeboom et al., 2008). To the south, Texas A&M AgriLife Extension recommends planting pearl millet, sorghum-sudan, and sudangrass between April 1st and June 1st (Corriher, 2013). However, they recommend a narrower window for planting forage sorghum from April 15th to June 1st. The University of Nebraska-Lincoln recommends planting dates for forage sorghum, sorghum-sudan, sudangrass, and pearl millet of May 15th to August 1st (Drewnoski & Redfearn, 2017). To the east, the University of Missouri-Columbia Extension recommends planting sorghum-sudan between May 1st and June 30th, while they recommend planting pearl millet between May 1st and June 15th (Kallenbach et al., 2001). Oklahoma State Extension recommends planting cowpea between May 1st and June 30th (Caddel & Enis, 2017).

Maturity at harvest

As a forage becomes more mature, forage quality decreases and biomass yield increases (Holman et al., 2018b; Bhattarai et al., 2019). In a study analyzing forage sorghum and sorghum-sudan at boot, heading, flowering, and dough stage, yields were highest at the dough stage. However, there was no significant difference between the other three stages (Holman et al., 2018b). Crude protein decreased as maturity progressed.

Snyman and Joubert (1996) found that when comparing forage sorghum at boot, flowering, and physiological maturity, yield and in-vitro digestible dry matter were maximal at the flowering stage, while crude protein content was maximal at both the boot and flowering stage. Forage sorghum harvested at physiological maturity was lower in overall quality than that harvested at boot or flowering.

Oskey et al. (2023) found that dry matter yield in pearl millet was higher when harvested at the heading stage as compared to the boot stage for the first cut. However, when a producer took a second cut from regrowth, the pearl millet that was originally harvested at boot stage had a higher second cutting yield than the pearl millet that was originally harvested at heading stage. They also found no difference in nutrient content between the two stages, except for an increase in dry matter percentage and ash as maturity increased.

Fertility Recommendations

Holman et al. (2019) found that the maximum dry matter yield of forage sorghum occurred at an N application rate of 100 kg N ha^{-1} (including soil N), but that the economic optimum application rate ranged between 55-70 kg N ha^{-1}, depending on the sorghum hay price and nitrogen fertilizer cost. They also found that application rates greater than 70 kg N ha^{-1} were likely to produce forage above the safe level of nitrates, so they recommended N application

rates of between 55-70 kg N ha^{-1} for dryland forage sorghum hay production. Split applications are recommended to reduce the potential of nitrate or prussic acid toxicity (Roozeboom et al., 2008)

In very high pH soils, iron and zinc deficiencies are a concern for forage sorghum, so iron and zinc chelate may need to be applied under high soil pH conditions (Bean & Marsalis, 2010). Applications of P and K should be based on a soil test; however, in the absence of a soil test, general recommendations are 34-90 kg ha^{-1} of each, either applied pre-planting or banded at planting (Bean & Marsalis, 2010; Roozeboom et al., 2008). If soil pH is less than 5.5, then applying lime is recommended (Roozeboom et al., 2008).

Pest control and tillage operation effects

Summer annual forage grasses generally grow rapidly and should be competitive with weeds that emerge after seeding (Roozeboom et al., 2008). However, there are some differences between species. Lenssen et al. (2011) found that plots seeded with foxtail (Setaria italica L.) or proso (Panicum mileaceum L.) millet had a higher weed density and weed biomass than plots seeded with sorghum-sudan. They also found that weed seed production by redroot pigweed and green foxtail was, respectively, 93% and 73% less in plots seeded with sorghum-sudan than in plots seeded with proso millet.

Few herbicides are explicitly labeled for application on summer annual forages. Atrazine can be applied to the soil or foliage for broadleaf weed control in summer annual grasses (Roozeboom et al., 2008; Bean & Marsalis, 2010). Herbicides listed for grain sorghum can generally be used on forage sorghum, but need to follow herbicide regulations. In non-Roundup Ready forage soybeans, cowpea, and lablab, preemergence Pursuit or Prowl can be used to control many warm-season annual weeds (Mississippi State University Deer Ecology &

Management Lab, 2019). No herbicides are labeled for sunn hemp production. However, research by Mosjidis and Wehtje (2011) identified pendimethalin, a preemergent herbicide, as a potential treatment that could provide adequate weed control during establishment.

All summer annual forage grasses are susceptible to cinch bug damage, particularly in the eastern portions of the Great Plains (Roozeboom et al., 2008). The best controls for chinch bugs are chemical. Mize et al. (1980) found that various formulations of carbaryl and carbofuran were effective in reducing chinch bugs. They also found that in-furrow treatments of carbofuran, terbufos, bendiocarb, and acephate at planting or seed treatments of carbofuran were equally effective in controlling cinch bugs. Carbofuran and bendiocarb provided the longest residual control of up to 30 days after planting. Band treatments of carbofuran effectively controlled chinch bugs if rain fell, but band treatments of phorate, terbufos, or disulfoton exhibited little or no insecticidal activity against chinch bugs.

Another pest of concern is greenbugs. Hackerott and Harvey (1970) found that foxtail, proso, and pearl millet were more resistant to greenbugs in terms of reduced plant injury and reduced survival and reproduction of greenbugs than forage sorghum was. They also found that pearl millet seedlings were slightly more resistant than mature pearl millet plants. Fortunately, greenbug-resistant cultivars of forage sorghum have been developed and have proven effective at reducing greenbug damage (Starks et al., 1983; Bramel-Cox et al., 1987; Kofoid et al., 1991; Andrew et al., 1993). All planting-time treatments used in Mize et al. (1980) against cinch bugs were also effective against greenbugs.

Holman et al. (2021b) found no significant difference in forage sorghum yield between a no-tillage treatment and a reduced tillage treatment. This result differs from Hassan et al. (2022), which found that conventional tillage had positive impacts on both forage yield and quality

attributes for sudangrass, pearl millet, and cowpea compared to reduced tillage and no-tillage treatments. Existing research suggests that the impact of tillage on grain sorghum yield is different than the impact tillage has on forage yield. Both Schlegel et al. (1999) and Obour et al. (2021) found that a reduced tillage treatment lowered grain sorghum yields in a wheat-grain sorghum-fallow rotation as compared to a no-tillage treatment.

Genetic traits of warm-season annual forages

An advantage of summer annual forages is that they have a wide variety of genetic traits that can significantly influence forage dry matter yield and nutritive content. This genetic variability enables producers to select forage varieties with traits that best align with their unique cropping system goals. The main genetic traits in summer annual forages are brown mid-rib (BMR), relative maturity, photoperiod sensitivity (PPS), dual-purpose, brachytic dwarf, dry stalk, sweet sorghum, and male sterile.

BMR trait

The BMR trait was first witnessed in corn in 1924 at the University of Minnesota farm (Eyster, 1926; Cherney et al., 1991). In 1975, Porter et al. used chemical mutagenesis to introduce the BMR trait into sorghum (Porter et al., 1978; Cherney et al., 1991). Then, in 1978, the BMR trait was backcrossed into sudan grass. Finally, in 1988, Cherney et al. (1991) used chemical mutagenesis to introduce the BMR trait into pearl millet.

When Porter et al. (1978) used chemical mutagenesis to introduce the BMR trait into sorghum, they created 19 BMR mutant lines. However, later research found only three of these lines to be agronomically viable: *bmr*-6, *bmr*-12, and *bmr*-18 (Fritz et al., 1990). The *bmr*-12 and *bmr*-18 genes are allelic, but *bmr*-6 is located at an independent locus from the *bmr*-12 and *bmr*-18 genes (Bittinger et al., 1981; Gupta, 1995). The *bmr*-6 gene has been shown to result in

shorter plants with less dry matter yield, without impacting ADL levels (Oliver et al., 2005). The *bmr*-12 gene resulted in reduced ADL and later maturity, with little to no impact on dry matter yield (Oliver et al., 2005). For these reasons, breeders prefer the *bmr*-12 gene over the *bmr*-6 gene (Oliver et al., 2005).

It is called the brown midrib trait because, in phenotypes with the trait, the midrib on the leaves contains a reddish-brown pigment (McCollum III et al., 2010). The BMR trait is recessive. When present in its homozygous state, the BMR mutation is associated with lower lignin content and higher digestibility (Porter et al., 1978; Cherney et al., 1986; Pedersen, J.F. 1996; Casler et al., 2003). However, there have been reports of yield reductions associated with the BMR trait. Casler et al. (2003) found that the yield of two BMR sudangrasses was 15% lower for the first cutting and 30% lower for the second cutting than that of their non-BMR counterparts. Hassanat (2007) observed a 50% decrease in total biomass yield in BMR pearl millet compared to non-BMR pearl millet. In a study that grouped multiple varieties of summer annual forage by trait class, Bean et al. (2013) found that, on average, the BMR forage sorghum class yielded 14% less than the non-BMR forage sorghum class.

Relative maturity

Typically, sorghum and pearl millet are short-day plants that require long nights before entering reproductive maturity stages (Craufurd et al., 1999). Several environmental factors control floral initiation, but day length is the most important (Morgan et al., 2002). The length of day that triggers flowering is controlled by seven genes in sorghum, designated as Ma1 through Ma7 (Quinby, 1974; Rooney et al., 2007; Mullet et al., 2012). However, in the 1960s, the USDA established a conversion program for sorghum to produce sorghum lines that were day length neutral. (Stephen et al., 1967). Nearly all sorghum varieties used in the United States are direct

descendants of lines developed from this program or other later conversion programs (Klein et al., 2016). This means that in hybrids descended from the lines developed through conversion programs, the accumulation of heat units is the primary driver of maturity, rather than day length. Thus, hybrids that are considered shorter-maturing require less accumulation of heat units than hybrids that are considered longer-maturing to flower.

Photoperiod sensitivity

The maturity groups described above are headed hybrids, meaning they flower before the end of the growing season (Staggenborg, 2019). Morgan et al. (2002) found that when both the Ma5 and Ma6 genes are present in their dominant form, they cause extreme lateness and delayed flowering; flowering will not initiate until day length is less than 12 hours and 20 minutes (McCollum III et al., 2010). In temperate environments, hybrids with the dominant form of the Ma5 and Ma6 genes typically do not produce panicles, and those that do produce grain will not be viable (Staggenborg, 2019). Thus, these varieties are often referred to as either "headless" or photoperiod-sensitive (PPS). While running sorghum variety trials in the Texas Panhandle, McCollum III et al. (2010) found that no PPS cultivars flowered before October 1st, and many did not flower by harvest in early to mid-October. Because of this increased time in the vegetative state, PPS sorghums typically outyield non-PPS sorghums (Bhattarai et al., 2019). Bean et al. (2013) found that PPS sorghum-sudan outyielded non-PPS sorghum-sudan by 30% and that dual-trait PPS-BMR forage sorghum outyielded BMR forage sorghums by 15%. PPS sorghums are less digestible and are higher in fiber than non-PPS varieties (McCollum III et al., 2010). Because of this and the fact that they produce no grain, PPS varieties are generally considered to have lower forage quality (Staggenborg, 2019). Bean et al. (2013) found that when comparing PPS sorghum-sudan to non-PPS sorghum-sudan and dual-trait PPS-BMR forage

sorghum to BMR forage sorghum, the PPS hybrids had lower CP, higher lignin, higher ADF, higher NDF, and lower IVTD than their non-PPS counterparts. In their study, varieties that produced grain were harvested at the soft dough stage, and PPS varieties were harvested simultaneously with the last varieties to reach soft dough.

Dwarfing traits

Four genes control sorghum height: *dw1*, *dw2*, *dw3*, and *dw4* (Rao & Goud, 1977). Genes *dw1* and *dw2* control internode length, *dw3* controls internode number, and *dw4* controls panicle length (Rao & Goud, 1977). Sorghums without the recessive form of any of these genes can reach over 4 m in height, so most grain sorghum hybrids have been developed to have the recessive version of the *dw1*, *dw3*, and *dw4* genes to facilitate easier mechanized harvest (Quinby & Karper, 1954; Staggenborg, 2019).

Dual-purpose sorghum hybrids are dwarfed forage hybrids that have the potential to be used for grain, ethanol conversion, hay, silage, or grazing depending on a farmer's needs and the influence of economic and environmental factors (Staggenborg, 2019; Yerka et al., 2015; Suad et al., 2015). They generally are intermediate in height between grain sorghums and traditional forage sorghums (Staggenborg, 2019). Because of the high grain content relative to other forage sorghum hybrids, they are high in starch. Thus, when used as silage, it is recommended to harvest between the milk and soft dough stages of development. If harvest is delayed past this point, the grain must be cracked or ground to be fully digestible to the animal.

Brachytic dwarf varieties have a combination of the recessive version of the genes that control internode length, resulting in shorter sorghum plants by reducing internode length (Elango et al., 2020; Staggenborg, 2019). Because the brachytic dwarf trait shortens the plant by reducing internode length, brachytic dwarf varieties have the same number of leaves as

traditional forage sorghums (Staggenborg, 2019). By reducing the stem length but leaving the same number of leaves, the brachytic dwarf trait increases the leaf-to-stem ratio of the plant. This increases the overall forage digestibility because leaves are higher in sugar and proteins, while stems are higher in non-digestible fibers (Pendleton & Seif, 1961; Staggenborg, 2019; Rocateli & Zhang, 2017). A secondary benefit of the brachytic dwarf trait is that it can reduce lodging, which is a common problem in traditional forage sorghums that can approach 4-5 m in height (Elango et al., 2020).

Dry-stalk trait

Breeders developed the dry-stalk trait to create forages that dry quicker when cut for hay in an effort to reduce spoilage (Noble Research Institute, 2018). Beck et al. (2007) found that when comparing a BMR sorghum-sudan with the dry stalk trait to a BMR sorghum-sudan without it, the hybrid with the dry stalk trait had a consistently higher dry matter percentage but reduced forage nutritive value due to lower CP and higher ADF and NDF. There were no significant forage mass differences between hybrids with and without the dry stalk trait (Beck et al., 2007).

Sweet sorghum trait

Sweet sorghum varieties are forage sorghums that have been selected for their high stem-juice yields and elevated sap-sugar concentrations (Staggenborg, 2019). Sweet sorghum hybrids consistently have a sugar content of more than 15% (Wu et al., 2010). Cultivars are structurally unique from other sorghum cultivars because instead of storing large amounts of complex carbohydrates in the grain, they store large amounts of non-structural carbohydrates in the stems (McBee et al., 1988). Sweet sorghum was initially used in the U.S. for human consumption as either crystal sugar or molasses (Staggenborg, 2019). However, there is evidence that sweet

sorghum could also be useful for forage purposes. Feeding sweet sorghum was found to result in similar daily weight gains as corn silage and greater average daily weight gains than fescue hay (Adewakun et al., 1989). Researchers found similar milk production in animals fed sweet sorghum compared to animals fed corn silage (Lance et al., 1964). Crude protein digestibility and gross energy digestibility were found to be higher in sweet sorghum than corn silage (Adewakun et al., 1989). Caswell et al. (1983) suggested that the greater amounts of sugar and ether extracts in sweet sorghum provide more readily available energy for animal performance. Sweet sorghum hybrids also were found to have higher starch content than other forage sorghum groups (Stefaniak et al., 2012)

An important note about sweet sorghum cultivars is that they have been primarily grown in the southeastern United States. Consequently, most of their genetic improvement has taken place in this water-rich region (Staggenborg, 2019). Studies conducted in south-central Nebraska (Wortmann et al., 2010) and northeastern Kansas (Propheter et al., 2010) have shown that water availability has a significant effect on forage production. This is a primary reason their use as forage is not common in semi-arid regions.

Male-sterile trait

Breeders originally developed male-sterile sorghums as a tool for producing large quantities of hybrid seed by cross-pollinating male-sterile female parents with a fertile male parent (Chen et al., 2019). Most grain sorghum varieties currently in use are hybrids produced using this method. However, recent research has suggested that male sterility may be a beneficial trait in forage sorghums. Duhatschek et al. (2023) found that male-sterile varieties have significantly greater water-soluble carbohydrate content and significantly less starch than non-sterile varieties. This tradeoff is caused by the fact that male-sterile varieties do not produce

grain; instead of translocating sugars to the grain and creating starch, as non-sterile varieties do, in male-sterile varieties, sugars remain in the vegetative part of the plant, resulting in higher overall sugar content. This means that farmers could potentially use male-sterile varieties to overcome concerns about starch digestibility associated with traditional forage sorghums. One concern with male-sterile varieties is inadvertent pollination from sorghum pollen that blows in the wind. This would negate the aforementioned benefits of male-sterile varieties. In small plot research, nearby pollinating varieties can easily pollinate male-sterile varieties, making their study somewhat challenging.

Genetic × environment × management interactions in forage production

There are often interactions between genetics, the environment, and management practices. One example of this is that forage species originating from warm, dry regions and equatorial regions have lower forage quality than those from temperate regions (Lee et al., 2018). Another example of this is that corn has higher yields and forage nutritive value than sorghum in environments with ample water; however, in water-limited environments, forage sorghum has outyielded corn and shown comparable forage nutritive value (Schittenhelm & Schroetter, 2014; Getachew et al., 2016).

There are also genetic and environmental interactions within species. In an irrigated management setting, McCuistion et al. (2010) found that forage sorghum PPS cultivars show the most rapid decline in forage quality as water application increased compared to non-PPS cultivars and dual trait PPS-BMR cultivars. They also found that BMR cultivars tend to maintain their forage quality better at increasing irrigation levels than non-BMR cultivars. These results suggest that further investigation into the relationship between environment, genetics, and management is warranted for summer annual forages.

Conclusion

The semi-arid Great Plains has a long and turbulent agricultural history, and the region continues to play an integral role in the nation's broader agricultural landscape. From the dryland wheat boom years of the early 20th century to the horrors of the Dust Bowl to the irrigation revolution and the resulting vertical integration of beef production to now facing a future with rapidly declining irrigation capacity, those who have wanted to make their living off the land of the semi-arid Great Plains have always needed to be adaptable. Forage production can play a crucial role in helping the region remain agriculturally productive and prosperous for years to come. The remainder of this thesis will identify specific ways summer annual forages, both grasses and legumes, can most effectively meet the agronomic and economic demands of the region through proper crop and seeding rate selection.

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Chapter 3 - Alternative summer-annual forage legumes

Abstract

Due to the decline of the Ogallala Aquifer and reduced irrigation capacity, there is growing interest in more water-efficient alternative forage crops in the semi-arid central Great Plains. One of the most water-intensive crops grown in the semi-arid central Great Plains is alfalfa (Medicago sativa L.). Alfalfa is grown for its high forage nutritive value, particularly crude protein, which cow-calf operators, feed yards, and dairies highly desire. The purpose of this study is to evaluate potential summer annual legume species as more water-efficient alternatives to alfalfa, while also possessing high forage nutritive value. This study sought to accomplish this by analyzing the viability, yield potential, nutritive value, water use efficiency, and economic returns of four summer annual legume species (cowpea [Vigna unguiculata], forage soybean [Glycine max (L.)], lablab [Lablab purpureus], and sunn hemp [Crotalaria juncea]) as well as two summer annual grass species (BMR forage sorghum [Sorghum bicolor (L.) Moench] and pearl millet [Pennisetum glaucum]). This study was conducted in 2022 and 2023 at three locations: Garden City, KS (irrigated), Colby, KS (dryland), and Hays, KS (dryland). Grasses generally had greater forage mass and had greater WUE than legume species. Lablab and cowpea were the only two legume species that did not face establishment challenges. Cowpea and forage soybean had significantly greater crude protein concentration (α =0.05) than either of the grass species, and cowpea, forage soybean, and lablab all had significantly greater relative feed quality (RFQ) values (α =0.05) than either of the grass species. Economic returns in irrigated environments were lablab = BMR forage sorghum = forage soybean = cowpea ≥ pearl millet ≥ sunn hemp (α =0.05), and in dryland environments were lablab = cowpea ≥ BMR forage sorghum ≥ pearl millet = forage soybean = sunn hemp (α =0.05). These results indicate cowpea

and lablab show the most potential of the tested summer annual legumes to serve as alternatives to alfalfa for the region.

Core ideas

- Summer annual grasses produced higher forage yields and were more productive than summer annual legumes, but summer annual legumes had higher crude protein concentrations and greater digestibility.
- When receiving similar levels of irrigation, forage soybeans, cowpeas, and lablab compared similarly or favorably to alfalfa in terms of forage yield, nutritive value, and economic profitability.
- Under dryland conditions, cowpea and lablab outperformed alfalfa in terms of forage yield and economic profitability within the semi-arid Great Plains region.

Introduction

Alfalfa is a highly sought-after crop in the animal feeding industry due to its high crude protein concentration and overall high forage nutritive value (Holman et al., 2016). Due to the semi-arid Great Plains' numerous feedlots and rapidly expanding dairy industry, alfalfa is a crucial crop in the region (Drouillard, 2018; Guerrero et al., 2012; Klocke et al., 2013). Because of its status as a high-quality forage and the large demand from the beef and dairy industries, when water is available for full irrigation of alfalfa, it is one of the most profitable crops in the region (Klocke et al., 2013). However, as the region's irrigation resources decline and because alfalfa's viability as a dryland crop in the region is limited, alternative high-quality forage crops are of interest to producers in the semi-arid Great Plains (Deines et al., 2010; Klocke et al., 2013).

Beyond concerns regarding irrigation capacity, there is a growing interest in forage-based cropping systems in the region due to their potential for increasing cropping intensity, productivity, and profitability (Holman et al., 2022; Nielsen et al., 2016). Alfalfa is a perennial plant and, consequently, is typically the only crop in rotation for an average of four to six years (Veronesi et al., 2010). This perenniality means alfalfa does not work well in a year-to-year cropping system, which limits a producer's flexibility. Thus, to develop robust forage-based cropping systems for the region, there is a need to identify viable, high-quality alternative annual forages. Some potential warm-season annual forage species include grass species such as BMR forage sorghum [Sorghum bicolor (L.) Moench] and pearl millet [Pennisetum glaucum] as well as legume species such as cowpea [Vigna unguiculata], forage soybean [Glycine max (L.)], lablab [Lablab purpureus], and sunn hemp [Crotalaria juncea].

The lines of forage sorghum used in the U.S. primarily originated in East and South Africa. (Bhattarai et al., 2019; de Wet & Huckabay, 1967). However, some original lines of sorghum also originated in North Africa, West Africa, the Middle East, and India, so modern hybrids may have inherited a portion of their genetic material from these regions as well. Due to its origin in a semi-arid climate, sorghum is a heat- and drought-tolerant crop that is well-adapted to semi-arid regions worldwide. It is a morphologically diverse species that includes many hybrids, although a few open-pollinated varieties are still grown. Forage sorghum will grow in soils of moderate fertility and grows best in soils of pH 6-7. It is not particularly tolerant of acidic or calcareous soils but performs better on heavier and wetter soils than pearl millet (Hanna & Sollenberger, 2007). Forage sorghum generally grows 2 to 4 m tall (Bhattarai et al., 2019). It uses significantly less fertilizer and water than corn but is highly responsive to N fertilization (Newman et al., 2013; Holman et al., 2019). However, sorghum silage is less energy-dense than corn silage (Bhattarai et al., 2019). Forage sorghums can exhibit the brown midrib trait (BMR), which is associated with lower lignin concentration and higher digestibility, resulting in an overall higher quality forage (Porter et al., 1978; Cherney et al., 1986; Pedersen, J.F. 1996; Casler et al., 2003). Forage sorghum yields can vary depending on climate, genetic variety, growth stage at harvest, fertility rate, and crop rotation. Holman et al. (2023) reported average forage yields of between 5,000 and 7,000 kg ha^{-1} over a seven year period for dryland forage sorghum near Garden City, KS. Under irrigated conditions near Clovis, NM, Marsalis et al. (2010) reported forage biomass yields of 24,400 kg ha^{-1} for non-BMR forage sorghum and 21,100 kg ha^{-1} for BMR forage sorghum.

Pearl millet is a morphologically diverse species that originated in northern Africa. It can grow up to 5 m tall, but most cultivars typically range from 2 to 3 m (Hanna & Sollenberger,

2007). Pearl millet is well suited to the semi-arid Great Plains because it thrives between 77-95 ºF (Marsalis, 2012). Bhattarai et al. (2020) found average forage yields of pearl millet under irrigated conditions when harvested at full maturity of 28,475 kg ha^{-1} in a study at New Deal, Texas. Kuhl et al. (1990) found average forage yields for pearl millet under dryland conditions near Pratt, KS of 4,606 kg ha^{-1} when harvested at boot stage and 9,245 kg ha^{-1} when harvested after heading. Pearl millet is sensitive to cold early in the growing season (Marsalis, 2012). Pearl millet is also known for its high water use efficiency (WUE), even in soils with low nutrient and moisture content, as well as its higher tillering potential and leafiness (Kumar, 1989; Singh et al., 2017; Marsalis, 2012). It grows best on well-drained loamy or sandy soils (Hanna & Sollenberger, 2007). An advantage of millet over forage sorghum is that it does not produce prussic acid, although recently developed forage sorghum germplasm was dhurrin-free (Tuinstra et al., 2016; Tuinstra et al, 2022). Dhurrin is a precursor to prussic acid, which can cause toxicity in livestock.

Cowpea is a drought-tolerant legume species that originated in sub-Saharan Africa and is used as both a vegetable crop for humans and as forage for livestock (Boukar et al., 2019; Smith et al., 2020). Forage cowpeas are widely used in Texas and the southeastern United States as wildlife food for white-tailed deer (Smith et al., 2020). In Africa, cowpea is primarily grown in dry savannahs and Sahel regions that receive less than 300 mm of rain a year (Boukar et al., 2019). Early in the semi-arid Great Plains' agricultural history, cowpeas were a more common crop than they are presently. Between 1,200 and 5,000 hectares were grown annually in Kansas from the early 1900s to the mid-1950s, but the area declined as farms became less diversified and increased the use of tractors and commercial nitrogen fertilizer (USDA National Agricultural Statistics Service, 1924-1956; Ten Eyck & Call, 1908). Cowpeas' drought and heat tolerance

make it an excellent candidate for reincorporation into Great Plains dryland cropping systems. Along with its drought tolerance, cowpea is also an ideal forage because it has a high nutritive value and does not cause bloat in ruminants (Caddel & Enis, 2017). Muir (2002) reported forage yields of cowpea under dryland conditions in north-central Texas of between 500 and 3,200 kg ha^{-1}.

Forage soybeans are the same species as grain soybeans, but they have been bred for forage potential instead of grain yield. They are typically used for short-season ensilage or hay, but they do not regrow after defoliation (Sollenberger & Collins, 2003). Yields increase with maturity until 75%-90% pod fill, after which leaf loss decreases yield and nutritive value. Soybean hay is difficult to cure and particularly susceptible to mold. Rao and Northrup (2009) reported soybean forage yields between 1,000 and 5,053 kg ha^{-1} over a four-year period at a dryland study near El Reno, OK. Yields were highly variable depending on in-season rainfall.

Sunn hemp is a tall annual legume originating on the Indian subcontinent (Mosjidis et al., 2012). In India, the plant is typically used for its fiber and occasionally as hay. However, it was introduced to the U.S. in 1899 for its ability to grow in low-fertility soils, its nematode resistance, and its capacity to increase soil organic matter, improve soil quality, and fix nitrogen. Interest in sunn hemp has increased in the U.S. recently because of its potential to serve as a summer cover crop and green manure. In the 20th century, concerns arose that sunn hemp forage might be toxic; however, further research has since shown that it is not. However, sunn hemp seeds in large doses can be toxic to livestock. Historically, due to its long growing season requirement, sunn hemp did not produce seeds in the temperate climates of North America; instead, seeds were shipped from South America to North America. However, a team of researchers at the University of Auburn developed cultivars in the early 21st century that produce

seeds suitable for temperate climates in North America. This has increased interest in the crop because it has made breeding and seed production feasible within the U.S., increasing the production of the crop. O'Shaughnessy et al. (2023) reported average irrigated sunn hemp forage yields of between 8,600 and 10,900 kg ha^{-1} at Bushland, Texas. In the Northern Great Plains, dryland sunn hemp forage yields of between 200 and 5,100 kg ha^{-1} and irrigated yields between 1,200 and 4,200 kg ha^{-1} were reported in a two-year study at Lingle, WY (Eberle & Shortnacy, 2021).

Lablab, also known as hyacinth bean, is widely cultivated in southern Asia and Africa, where its seeds and pods are used for human consumption (Stephens, 2018). The plant is also grazed. In the U.S., it is most commonly grown as an ornamental. It is a highly variable species with 20 to 50 botanical varieties (Pittman & Kretschmer, 2007). It is drought-tolerant and grows well in slightly acidic to alkaline soils. It is typically strip-grazed, with cattle eating only the leaves, and then they are removed to allow for regrowth. The leaves produce high-quality hay for cattle and goats, but the stems are difficult to dry and must be mechanically conditioned through crushing (FAO, 2012). The Rongai and Rio Verde varieties have been tested and proven viable in the semi-arid Great Plains (Carr & Rea, 2014). Northup & Rao (2015) reported an average forage yield of 1,415 kg ha^{-1} for dryland lablab near El Reno, OK for a four-year study in which growing season precipitation greatly impacted lablab forage yield year-to-year.

Along with forage mass, forage nutritive value is important element of evaluating forages. Forage nutritive value has a significant influence on realized livestock gains for a given amount of forage (Newman et al., 2007). Forage yield and nutritive value are generally inversely related, so it is often important to find a balance between the two (Cusicanqui & Lauer, 1999; Huang et al., 2020; Liebert et al., 2023). Multiple measures are available to evaluate forage

nutritive value, including concentrations of crude protein, fiber, and energy, as well as forage quality indices calculated using multiple individual measures.

Crude protein (CP) is measured by taking the total nitrogen content (as measured by the Kjeldahl digestion method) multiplied by 6.25 (Lee, 2018). Protein supplementation is the most expensive component in livestock feeding programs; therefore, forage crops with high crude protein content are highly desirable (Lemus, 2020). Crude protein can vary widely based on forage species, nitrogen fertility, and forage maturity. Generally, legumes are between 12%-25% CP, cool-season grasses are between 8%-23% CP, and warm-season grasses are between 5%-18% CP (Adesogan et al., 2017). As forages mature, crude protein content is diluted by increasing fiber, resulting in reduced nutritive value (Van Saun, 2023).

Fiber content is the best single predictor of feed intake and digestibility; therefore, fiber measures are also important for determining forage nutritive value (Lee, 2018). The two primary fiber measures are acid detergent fiber (ADF) and neutral detergent fiber (NDF). Acid detergent fiber represents the plant's structural components (lignin, cellulose, silica, and insoluble nitrogenous compounds, but not hemicellulose). It is determined by weighing what remains after boiling in acid detergent. Neutral detergent fiber is what remains after boiling in neutral detergent and includes lignin, silica, cellulose, and hemicellulose. As ADF percentage increases, digestibility will generally decrease, and as NDF percentage increases, total dry matter intake will generally decrease (Benedict, 2012). Consequently, high-quality forages will have both lower ADF and NDF values. For grasses and legumes, ideal ADF fractions are less than 35% (Van Saun, 2023). Regarding NDF, for grasses, an NDF fraction below 50% is considered high-quality forage, and an NDF fraction above 60% is considered low-quality forage. For legumes, an NDF fraction below 40% is considered good, and above 50% is considered poor.

Occasionally, lignin content is measured independently because it can have a significant impact on forage quality. Sometimes referred to as the "woody part" of a plant, lignin is the primary factor influencing cell wall digestibility (Benedict, 2012). As lignin increases, digestibility, intake, and animal performance all decrease. Lignin content is primarily based on species and maturity (Kondo et al., 1987). As plants mature, their lignin content increases; in general, woody species, such as trees and shrubs, contain higher levels of lignin than grass species and legumes.

There are many different measures to quantify the total energy value of a forage. Total digestible nutrients (TDN) has been used for many years and is one of the most easily understood and widely recognized forage nutritive values (Adesogan et al., 2017). It is calculated as the sum of digestible protein, digestible crude fiber, digestible nitrogen-free extract, and 2.25 times the digestible fat concentration. Higher TDN values indicate a higher quality forage, and TDN decreases as a plant matures.

Because there are many different measures of forage nutritive value, there have been a handful of efforts to index the various measures into a single value. The two most common indices are relative feed value (RFV) and relative forage quality (RFQ). RFV is the older of these two indices and uses NDF and ADF as predictors of forage quality (Adesogan et al., 2017). RFV ranks the quality of a cool-season forage relative to alfalfa at full bloom. The RFV of alfalfa at full bloom equals 100, so RFVs greater than 100 would be considered a higher quality forage than alfalfa at full bloom, and RFVs less than 100 would be a lower quality forage than alfalfa at full bloom. Because alfalfa is a temperate cool-season forage, RFV should be used only to evaluate other temperate cool-season forage species. RFQ is a newer index designed to apply to all forages (cool-season, warm-season, and tropical) except corn silage. It has the same mean

and range as RFV, so it can be substituted for RFV when necessary. However, RFQ is based on CP, NDF, ADF, fat, ash, and NDFd, so comparing RFQ scores with RFV scores should be avoided whenever possible.

The objective of this study was to evaluate the viability, yield potential, water use efficiency (WUE), forage nutritive value, and profitability of these six species under both dryland and irrigated environments. We hypothesized that the grass species would have higher forage yields and WUE than the legume species but would be lower in crude protein and higher in fiber, resulting in an overall lower quality (Cherney et al., 1991; National Drought Mitigation Center, 2024; Adesogan et al., 2017; Van Saun, 2023). We also expected that some, but not all, of the legume species tested will prove to be viable, high-quality potential alternatives to alfalfa for the region.

Materials and Methods

Experimental layout

We established this study in 2022 and repeated it in 2023. The study took place in three locations. One site was in Garden City, KS, at the K-State Southwest Research-Extension Center (37.9856018, -100.8140431). The second site was at the K-State Northwest Research-Extension Center in Colby, KS (39.381769, -101.0654100). The third site was at the K-State Agricultural Research Station in Hays, KS (38.8510173, -99.3428914). The Garden City site was irrigated, whereas the other two sites were not.

All three sites are in the semiarid Central Great Plains region. The Garden City site has a 60-year average precipitation of 477 mm, the Colby site has a 60-year average precipitation of 495 mm, and the Hays site has a 60-year average precipitation of 585 mm (Table 3.1). In 2022, we applied 318 mm of irrigation in Garden City between planting and final harvest. On June

30th, July 8th, and July 20th, 38 mm of irrigation were applied; 25 mm were applied on August 3rd, 9th, 19th, and 26th as well as September 1st, 9th, 15th, and 26th. In 2023, due to increased precipitation, we reduced the total irrigation amounts between planting and final harvest to 102 mm. On July 18th, July 26th, July 31st, and August 17th, 25 mm were applied.

In Garden City, the soil series was Ulysses Silt Loam, with slopes ranging from 0 to 1 percent. In Colby, the soil series was Keith Silt Loam, with slopes ranging from 0 to 1 percent. In Hays, the soil series was Crete silty loam, with slopes ranging from 0 to 1 percent. The study was a randomized complete block design with four replications of the following species: BMR forage sorghum, pearl millet, cowpea, lablab, forage soybean, and sunn hemp. In 2022, lablab was inadvertently not planted in Garden City or Hays. We planted all other species at all sites and all years. Any missing data, for species other than lablab, was due to establishment challenges. In Garden City and Hays, plots were 9 m × 5 m, and in Colby, plots were 3 m × 15 m.

Crop management

All forage species were planted to a depth of 25.4 mm and in rows spaced at 203.2 mm in Garden City and Hays. In Colby, we planted with 254 mm row spacing. Planting dates ranged from May 30th to July 31st (Table 3.2). In Colby, a Great Plains 6P305NT no-till drill was used to plant the crops (Great Plains, Salina, KS). In Garden City, we planted with a Fabro no-till plot drill (Fabro, Swift Current, Canada). In Hays, we planted with a Great Plains 3P1006NT no-till drill (Great Plains, Salina, KS). All legume species were planted at a seeding rate of 44.8 kg ha^{-1}, BMR forage sorghum was planted at a rate of 16.8 kg ha^{-1}, and pearl millet was planted at a rate of 13.5 kg ha^{-1} (Kilgore, 1998; Fjell et al., 1998).

Approximately a month before planting, all plots received a burndown treatment of 0.15 L ha^{-1} of saflufenacil, 2.4 L ha^{-1} of glyphosate [*N-(phosphonomethyl) glycine*], and 2.4 L ha^{-1} of

methylated seed oil (MSO). The legume plots also received a separate pre-planting application of pendimethalin at a rate of 3.6 L ha^{-1} for residual weed control. In contrast, the grass species received a pre-planting application of atrazine at a rate of 2.4 L ha^{-1} for the same purpose. All plots received 56.1 kg ha^{-1} application of mono-ammonium phosphate (MAP, 11-52-0) at planting. Grasses received an additional application of urea fertilizer (46-0-0) at a rate of 50.5 kg ha^{-1}. In total, legumes received 6.2 kg ha^{-1} of nitrogen and 29.2 kg ha^{-1} of phosphorus, and grasses received 29.4 kg ha^{-1} of nitrogen and 29.2 kg ha^{-1} of phosphorus.

Harvest techniques and timings

Harvests were conducted by hand using a 1 × 1 meter square and a cutting height of 76 mm. It is possible that, because we conducted the harvests by hand, the reported yields are higher than they would typically be for a machine harvest. This is because mechanical forage harvesters leave a portion of the cut material on the ground, resulting in lower measured yields. Whereas, when hand harvesting, nearly all of what is cut is included in the measured yield. In Garden City, forage sorghum and pearl millet were harvested at the boot, anthesis, soft dough, and kernel hard stages (Vanderlip & Reeve, 1972). The original plan was to harvest all legumes at the R1 (begin flowering), R3 (begin podding), R5 (begin pod fill), and R7 (begin maturity) stages (Fehr & Caviness, 1977). However, only forage soybeans in both 2022 and 2023, and cowpeas in 2022, progressed to R7 before the first freeze occurred. Sunn hemp did not progress past R1 in either year, so we harvested it only twice. We conducted the first harvest when a majority of the plants in a plot reached the R1 stage, and the second at the end of the growing season. For this study, an "end of season" harvest refers to harvests conducted in the days immediately following the first fall freeze of the year. In the one year lablab was planted in Garden City, it did not reach R1, so it was harvested at the end of the growing season while it was still in a vegetative stage.

Although cowpea reached R7 in 2022, in 2023 it only reached R1, which occurred three days before the first freeze. Consequently, the R1 harvest was the only cowpea harvest taken in 2023. We hypothesize that the difference in maturity progression in cowpea between 2022 and 2023 was due to seed quality, because the same variety of cowpea (Iron & Clay), although from different seed lots, was planted in both years (Table 3.3). In Colby and Hays, only one harvest was taken, at the end of the growing season. This end of season harvest occurred approximately at the early grain fill stage in the grasses, at R1 in sunn hemp, at R7 in forage soybean, and in a vegetative stage for cowpea and lablab.

To determine the forage mass, the weight of the entire fresh biomass within a 1 × 1 meter square was measured. Then, a 0.7 kg sub-sample of the freshly harvested forage was dried for at least 48 hours until weight remained constant (at 104º F in Garden City and 140º F at the other locations), and the dry weight was divided by 0.7 (the fresh weight of the sample) to calculate a percentage dry matter. This percent dry weight was multiplied by the fresh weight of the 1 × 1 square meter sample to find the forage dry matter biomass yield of the 1 × 1 square meter. We scaled this forage mass up to kg ha^{-1}.

Soil water content measurements

At all site-years, except Hays in 2023, soil water content was calculated based on the readings of a CPN Neutron Probe (model number 503 DR, CPN, Concord, CA). In Colby, we calculated neutron probe readings in 0.3 m increments to a depth of 2.4 m. In Garden City, we collected neutron probe readings in 0.3 m increments to a depth of 1.8 m. In Hays, we collected neutron probe readings in 0.3 m increments to a depth of 1.2 m. Due to differences in the depth of the neutron probe readings, irrigation, and soil types, water use efficiency data were analyzed separately for each site. We took these readings at the time of planting and whenever a harvest

occurred. Neutron probe readings were converted into volumetric water content based on their local calibration and then into plant available water using the following equation:

Plant-Available Water = (Volumetric Water Content – Permeant Wilting Point) x 30

Each location had its own previously calculated permanent wilting point based on its soil type. We calculated the total profile PAW by summing the PAW for each depth increment. In Hays 2023, the gravimetric method was used instead of a neutron probe to estimate PAW (Schmugge et al., 1980).

We calculated water use using the following formula:

Water Use = PAW at planting – PAW at harvest + (Irrigation + Precipitation)

We calculated water use efficiency (WUE) by dividing forage mass by water use.

WUE (kg $ha^{-1}mm^{-1}$ of water) = forage yield (kg ha^{-1}) ÷ water use (mm)

Forage nutritive analysis

Only the samples from Garden City were analyzed for forage nutritive value. After being dried and weighed, samples were ground using a Wiley Mill fitted with a 2-mm screen (model number T4724E25, Thomas Scientific, Chadds Ford Township, PA), then with a UDY Cyclone Sample Mill fitted with a 1-mm screen (model number 3010-014, UDY, Fort Collins, CO). The ground samples were analyzed for crude protein (CP), acid-detergent fiber (ADF), neutral detergent fiber (NDF), lignin, and starch using NIR (near infrared) spectroscopy calibrated to NIRS Consortium standards for either warm-season annual grasses or warm-season annual legume species. Total digestible nutrients (TDN) and relative forage quality (RFQ) were calculated using the other measured forage nutritive values (Weiss, 1998; Moore & Undersander, 2002). We did not conduct forage nutritive analysis on samples from Colby or Hays because harvesting at the end of the growing season resulted in inconsistent growth stages across

treatments, thereby confounding the effects of growth stage and treatment. We calculated CP and TDN yields by multiplying the CP and TDN concentrations by the forage yield.

Economic analysis

Economic returns for each species were calculated for Garden City using yield data from 2022 and 2023 and for Colby using 2022 yield data. Yield data collected in 2023 at Colby was excluded from the economic analysis because, in 2023, we planted crops at Colby later than they generally would under normal planting conditions, leading to low yields, and weeds choked out the forage soybean crop. Hays was excluded from the economic analysis because it had missing species in both years due to establishment challenges.

A partial enterprise analysis was determined for each species by subtracting production cost from the harvested crop value (Table 3.4). We obtained the production costs of drilling, swathing, baling, stacking, herbicide application, and fertilizer application from the statewide values provided in the 2022 Rates Paid by Kansas Farmers for Custom Work, published by the Kansas Department of Agriculture and the Kansas State Land Use Survey Office (AgManager, 2022). We obtained seed cost from the websites of various regional seed companies (Green Cover, 2024; Albert Lea Seed, 2024; Merit Seed, 2024; Browning Seed, 2024). We obtained herbicide prices from the K-State Research and Extension 2024 Chemical Weed Control book (Lancaster et al., 2024). We obtained fertilizer prices from the Kansas AgManager Forage Sorghum Hay Cost-Return Budget (Ibendahl et al., 2023a). We obtained irrigated and non-irrigated land rental prices from the Kansas County-Level Cash Rental Rates for Irrigated and Non-Irrigated Cropland reports (Ibendahl & O'Brien, 2023a; Ibendahl & O'Brien, 2023b). We calculated the cost of irrigation by summing the irrigation energy and labor components from the

Irrigated Alfalfa (Center-Pivot) Cost-Return Budget under the low-yield scenario (Ibendahl et al., 2023b).

We calculated the crop value by multiplying forage yields for each species by the hay price. We expressed these values on a per-hectare basis. We obtained hay prices from the average reported price of the first USDA Southwest Kansas Direct Hay Reports published each month in the years 2022 and 2023 (USDA Agricultural Marketing Service, 2022-2023). For grass hay, we used the price for good-quality Sudan hay. The legume hay prices were based on each legume's RFQ value. Legumes with RFQ values greater than or equal to 185 were classified as supreme quality alfalfa hay; legumes with RFQ values between 170 and 184 were classified as premium quality alfalfa hay; legumes with RFQ values between 150-169 were classified as good quality alfalfa hay; legumes with RFQ values between 130-149 were classified as fair quality alfalfa hay; legumes with RFQ values less than 130 were classified as utility quality alfalfa hay. Because we did not conduct a forage nutritive analysis on samples from Colby, we determined the hay quality of the species in Colby by matching the growth stage at which each species was harvested in Colby to their corresponding growth stage and subsequent hay quality in Garden City. We considered the sunn hemp in Colby to be fair quality legume hay because when we harvested in Colby, it was at a growth stage approximately in between the first harvest of sunn hemp (good quality legume hay) and the second harvest of sunn hemp (utility quality legume hay) in Garden City.

To make comparisons to alfalfa profitability we used the results of Holman et al. (2016) because their study included both irrigated and dryland alfalfa treatments in Garden City, KS meaning their study had a comparable environment to ours. However, Holman et al. (2016) used a less extensive budget to estimate profitability than we did. In our budget, we included drilling,

seed, swathing, stacking, herbicide, and land rent costs. Holman et al. (2016) did not include any of these expenses. Therefore, we used the Kansas State University Ag Manager irrigated alfalfa crop budget, land rental rates, and custom rates survey and the same USDA hay reports used to estimate annual legume profitability along with the reported yields from Holman et al. (2016), to estimate alfalfa profitability and make relevant comparisons to the legumes in our study (Ibendahl & O'Brien, 2023a; Ibendahl & O'Brien, 2023b; Ibendahl et al., 2023a; AgManager, 2022; USDA Agricultural Marketing Service, 2022-23). Fertilization rates were taken from Holman et al. (2016). To estimate dryland alfalfa profitability, irrigation costs were removed from the irrigated alfalfa budget, and non-irrigated land rents were used.

Statistical analysis

Analysis of variance for forage mass, water use, water use efficiency, forage nutritive values, and economic returns was performed using PROC GLIMMIX in SAS Studio ver. 3.82 (SAS Institute, 2023, Cary, NC). In all models, species, year, location, and growth stage at harvest were considered fixed effects when applicable. Replication and its interactions were considered random effects. Growth stage at harvest was treated as a repeated measure in our model. The 2022 cowpea and 2023 cowpea data were analyzed separately because of extreme differences in maturity progression between the two years. We considered species' main effects significant at $P \leq 0.05$. Means were separated using Tukey's method for multiple comparisons. Pearson correlation coefficients among response variables were generated using PROC CORR.

Results

Weather

In 2022, precipitation was well below the 60-year average for all three sites (Table 3.1). In 2023, precipitation was above the 60-year average in Colby and Garden City. In Hays, total

annual precipitation increased from 2022 to 2023 but was still below the 60-year average. However, in 2023, delayed planting at Colby and replanting due to herbicide damage at Hays resulted in all species not being planted until late July at both dryland locations (Table 3.2). Consequently, the dryland trials in 2023 did not have the opportunity to take full advantage of the improved precipitation in 2023.

Establishment and yield

No species faced establishment challenges in Garden City, but we did not plant lablab in Garden City in 2022 (Table 3.3). In Colby, all species established in 2022, but in 2023, three of the four forage soybean replications were choked out by weeds, resulting in yields near zero. Consequently, we did not analyze the 2023 forage soybean data from Colby. At the Hays site, both sunn hemp and forage soybean failed to establish in 2022 (lablab was not planted). In 2023, sunn hemp again failed to establish at Hays. Cowpea and lablab were the only two legume species that consistently established in both years at Hays.

At all three locations in both years, a grass species produced the greatest forage mass (Table 3.5). Forage sorghum yielded more than pearl millet at Garden City in 2023 and at Hays in 2022. Under irrigation, pearl millet significantly out-yielded all legume species. However, in dryland conditions, pearl millet yielded similarly to cowpea in Hays 2022, lablab in Colby 2022, and all legumes in 2023 at Colby. For both grass species, delaying harvest until the later stages of maturity (soft dough and kernel hard) resulted in greater forage mass than the earlier stages (boot and anthesis) (Table 3.6).

Among the legume species, there was not a single site-year in which one legume species significantly out-yielded any other legume species (Table 3.5). However, some trends that were not statistically significant did emerge at the dryland sites. Under dryland conditions, forage

soybeans were the lowest-yielding legume species whenever it established, and lablab was the highest-yielding legume species whenever it was planted. At both dryland sites, forage mass was lower in 2023 than in 2022. This was most likely caused by delayed planting at Colby and replanting of the legumes due to herbicide damage at Hays in 2023 (Table 3.2). In Garden City, while there was a significant species-by-year interaction, year had no significant effect on yield.

The growth stage at harvest had a significant effect on yield for all legume species except forage soybean (Table 3.6). The relationship between forage yield and growth stage was particularly complex in cowpea. In 2022, when cowpea reached the R7 growth stage before the first freeze, the relationship between growth stage and yield was as follows: R5 ≥ R7 = R3 ≥ R1. However, in 2023, when cowpea reached only R1 before the first freeze, forage mass at that R1 cutting was 79% greater than the highest yielding stage in 2022. An early freeze did not cause cowpea's lack of progression through its maturity stages in 2023. In 2022, cowpea reached R1 on September 14th, while in 2023, it did not reach R1 until October 4th (Table 3.3). This was despite the fact that planting occurred more than two weeks earlier in 2023 than it did in 2022 (Table 3.2). This suggests that the difference in maturity progression was most likely due to either differences in seed quality or genetic variety differences, most likely related to photoperiod sensitivity. We suspect that, although we used the same variety of cowpea (Iron & Clay) from the same seed dealer in both years, the variety grown in 2023 was possibly not Iron & Clay. The seed quality and genetic purity of these minor crops are often not as precise as those of major commodity crops. Regardless, the results clearly indicate that the longer cowpeas remained in a vegetative stage, the greater their overall forage mass. This suggests that using later-maturing varieties of cowpea may increase cowpea forage yield.

Sunn hemp and forage soybean maintained consistent maturity progressions in 2022 and 2023. Sunn hemp behaved similarly to the grass species, with forage mass at end-of-season cutting being significantly greater than the R1 cutting (Table 3.6). Growth stage at harvest did not have a significant effect on forage mass in forage soybean. Similar to cowpea in 2023, lablab remained vegetative until the end of the season and consequently exhibited one of the highest forage masses of all the legume species.

Water use

The relationship between total growing season water use and species was highly dependent on the environment (Table 3.7). In four of the six site-years, there was no significant difference in water use between species. The two exceptions are Colby 2023, which had the lowest combined PAW at planting and in-season precipitation of any of the trials, and Garden City 2023, which had the greatest combined PAW at planting and in-season precipitation and irrigation (Table 3.2).

At Colby in 2023, the two grass species used significantly more water than sunn hemp and, on average, more water than the other legume species (Table 3.7). This result suggests that in very low-yielding, low-water environments, grass species may use more water than legume species because they continue to produce biomass under challenging growing conditions. On the other end of the spectrum, at Garden City in 2023, where ample water was available, and yields were high, both sunn hemp and forage soybean used significantly more water than BMR forage sorghum or pearl millet. Cowpea and lablab both used more water than the two grass species, although the difference was not significant.

In summary, water use correlated strongly with water availability (Table 3.8). As water availability increased, water use increased. In every environment, except the wettest and driest

environments, the total water use among species was not significantly different (Table 3.7). This result suggests that, when water is neither severely limited nor in significant excess, all species will use about the same amount of water. However, in very water-limited environments, such as Colby 2023, grass species may use more water because the legumes produce so little biomass that they do not use much water. Conversely, in environments with high water availability, such as Garden City 2023, legumes generally used more water than grass species, most likely because it takes more water to produce forage with greater crude protein concentration (Table 3.7) (Núñez et al., 2022).

The relationship between water use and growth stage was clear-cut. As maturity progressed, water use increased, in all cases at a statistically significant level (Table 3.9). Also, when we analyzed the mean water use across growth stages, water use increased for all species between 2022 and 2023 in Garden City. The total PAW at planting and in-season water received was greater in 2023 than in 2022 (Table 3.2). This increase in total water use between 2022 and 2023 at Garden City further confirms that, as water availability increased, water use increased, and as water use increased, forage yield increased (Table 3.8).

Water use efficiency

BMR forage sorghum had significantly greater WUE than all legume species in all environments except for lablab at Hays and Colby in 2023 (Table 3.10). Pearl millet had a greater WUE than all legume species in all site-years (except for cowpea at Hays in 2022), but it was not always a statistically significant difference. Generally, BMR forage sorghum had greater WUE than pearl millet (5 of 6 site-years), but it was only statistically significantly greater in three environments: Garden City 2023, Colby 2022, and Hays 2022. Overall, grasses used water more efficiently than legumes (Table 3.8).

Among the legume species, there were no statistically significant differences in terms of WUE within a site-year. However, whenever forage soybeans were able to establish in a dryland environment (Colby 2022 and Hays 2023), they had the lowest WUE among the legume species. When present, lablab was always either the most or the second-most water-use-efficient legume species (Table 3.10). Legume WUE declined sharply between 2022 and 2023 in dryland locations. The most likely explanation for this is reduced yields resulting from the delayed planting that shortened the growing season in both Hays and Colby in 2023 (Table 3.2). WUE was more strongly correlated with yield than water use (Table 3.8).

In the relationships between WUE and growth stage, we see varied responses from the different species (Table 3.11). In 2022, BMR forage sorghum WUE displayed the following relationship: anthesis = soft dough ≥ boot = kernel hard. In 2023, BMR forage sorghum WUE had the following relationship with growth stage: soft dough = kernel hard = anthesis > boot. Based on this information, BMR forage sorghum WUE peaks somewhere between the anthesis and kernel hard stage.

Water use efficiency was not significantly different across the various growth stages of pearl millet, sunn hemp, and forage soybeans. This result suggests that, as yield increases with maturity in these species, water use increases at an approximately corresponding rate. In 2022, cowpea exhibited the same behavior as these other three species, with no significant differences in WUE between the different growth stages. However, the single harvest of cowpea at the R1 stage in 2023 had a WUE at least 48% greater than the WUE of any of the growth stages in 2022. This result suggests that later-maturing varieties of cowpea, which remain in a vegetative stage for a longer portion of the growing season, will have greater WUE than cowpea varieties that mature more quickly. Based on the similarities in water use and yield between 2023 Garden

City cowpea and lablab, later maturing lablab varieties likely also have greater WUE than early maturing varieties.

Forage nutritive values

Forage nutritive values varied greatly by species. To make comparisons among species, the forage nutritive values for a species were taken from an average across all its harvests throughout the growing season. The crude protein concentration differences among species had the following relationship: lablab = 2022 cowpea = forage soybean = 2023 cowpea ≥ sunn hemp = pearl millet > BMR forage sorghum (Table 3.12). The relationship between starch concentration and species was as follows: 2023 cowpea > 2022 cowpea = BMR forage sorghum > forage soybean = pearl millet = lablab. The differences in ADF concentration among species were as follows: sunn hemp = pearl millet > BMR forage sorghum ≥ 2023 cowpea = forage soybean = 2022 cowpea = lablab, and for NDF concentration was pearl millet > BMR forage sorghum > sunn hemp > 2023 cowpea = 2022 cowpea = forage soybean = lablab. The grass species had significantly greater NDF concentration than legume species, but the relationship for ADF concentration was less clear. Pearl millet had significantly greater ADF and NDF concentrations than BMR forage sorghum, and sunn hemp had significantly greater ADF and NDF concentrations than all other legume species. Sunn hemp is known to have high fiber concentrations, and this study confirms that finding (Lepcha et al., 2019). Lignin concentrations followed this pattern: sunn hemp > forage soybean = 2023 cowpea = 2022 cowpea = lablab > pearl millet > BMR forage sorghum. When averaged across all legume species, legumes had 67.6% greater lignin concentration than pearl millet and 181.3% greater lignin concentration than BMR forage sorghum. Sunn hemp had a significantly greater lignin concentration than all the

other legume species, averaging a 45.6% greater lignin concentration than the other three legumes. The BMR forage sorghum had a 40.4% lower lignin concentration than pearl millet.

The next forage nutritive value we evaluated was TDN, which is a measurement of forage energy content (Adesogan et al., 2017). The relationship among species for TDN was as follows: BMR forage sorghum > forage soybean = lablab = 2022 cowpea = 2023 cowpea > pearl millet > sunn hemp. The final forage nutritive value we analyzed was RFQ, an index that aims to compare digestibility and intake among forages (Adesogan et al., 2017). The relationship among species for RFQ values was as follows: forage soybean = lablab = 2022 cowpea ≥ 2023 cowpea > sunn hemp = BMR Forage sorghum > pearl millet. In summary, the relationship between TDN and species does not appear to be strictly based on whether a species is a grass or a legume. However, all legume species had greater RFQ values than the two grass species, with forage soybean, lablab, and both years of cowpea having significantly greater RFQ values than both grass species, and sunn hemp having a significantly greater value than only pearl millet. Sunn hemp had a significantly lower TDN concentration and RFQ value than all other legume species. BMR forage sorghum had an 11.7% greater TDN concentration and a 22.2% greater RFQ value than pearl millet.

The impact of growth stage on forage nutritive value varied by species and the various forage nutritive measures. In all species, CP generally declined as maturity increased, but only significantly so in pearl millet, 2022 cowpea, and sunnhemp. In pearl millet, the relationship between growth stages and CP concentration was as follows: boot > anthesis > soft dough = kernel hard, with a 53% total reduction between boot stage and kernel hard. In sunn hemp, there was a 51% reduction in CP concentration between R1 and the end-of-season harvest. In 2022 cowpea the relationship between growth stage at harvest and CP concentration was as follows:

R1 = R3 ≥ R7 = R5. Interestingly, the 2023 R1 harvest had a CP concentration more similar to the later growth stage harvests in 2022, specifically R5 and R7, than it did at the corresponding stage of R1. This result could be because generally, yield and crude protein concentration are inversely related, and the 2023 R1 harvest had a much greater forage yield than the 2022 harvest (Table 3.6) (Moyer et al., 2003). In both BMR forage sorghum and forage soybean, while the earlier growth stages had greater crude protein concentrations than the later growth stages, there were no significant differences between the growth stages.

BMR forage sorghum, pearl millet, cowpea, and sunn hemp all had significant interactions between growth stage and species regarding starch concentration (Table 3.12). In all four species, starch increased as maturity progressed. This was likely due to seed production. BMR forage sorghum and 2022 cowpea had much larger increases in starch concentration as maturity progressed than pearl millet or sunn hemp did suggesting BMR forage sorghum and 2022 cowpea had higher rates of grain fill than pearl millet or sunn hemp.

The effect growth stage at harvest had on the fiber measures of ADF, NDF, and lignin concentration varied by species. For BMR forage sorghum, 2022 cowpea, and forage soybean, growth stage at harvest did not have a significant effect on any of these fiber measures (Table 3.12). In pearl millet, these fiber measures significantly increased as the plant matured. The ADF increased 14.5% between boot and kernel hard, NDF increased 12.7% between boot and kernel hard, and lignin increased 47.3% between boot and kernel hard. Sunn hemp behaved similarly to pearl millet, with a significant increase in ADF, NDF, and lignin concentration between the R1 and the end-of-season cutting.

Growth stage had a significant effect on TDN only in BMR forage sorghum and sunn hemp. In BMR forage sorghum, TDN was significantly greater at the soft dough and kernel hard

stages than at the boot stage. In sunn hemp, R1 had a greater TDN than at the end of the season. Development stage had a significant effect on RFQ in pearl millet and sunn hemp. In pearl millet, the relationship between RFQ and growth stage was boot = soft dough = anthesis ≥ kernel hard. For sunn hemp, the R1 harvest had a 78% greater RFQ value than the end of the season harvest. The growth stage at harvest did not have a significant effect on TDN or RFQ in either 2022 cowpea or forage soybean, although the R1 stage did have the greatest RFQ value in both species.

Nutritive value per area

Crude protein yield had the following relationship among the species across growth stage at harvest and year: lablab = 2023 cowpea = BMR forage sorghum ≥ pearl millet > forage soybean = 2022 cowpea = sunn hemp (Table 3.13). The only species with a significant difference in CP yield by growth stage was pearl millet, where the soft dough stage had a significantly greater CP yield than the boot stage. While not compared statistically because of differences in maturity progression, the 2023 R1 cowpea CP yield was at least 81% greater than any of the 2022 cowpea harvests. This was primarily due to differences in forage yield between the two years, not differences in CP concentration (Table 3.6; Table 3.12).

Total digestible nutrient yield had the following relationship among the species across growth stage at harvest and year: BMR forage sorghum > pearl millet ≥ 2023 cowpea = lablab ≥ forage soybean = sunn hemp = 2022 cowpea (Table 3.13). BMR forage sorghum had the following relationship for TDN yield by growth stage: soft dough = kernel hard ≥ anthesis = boot. Pearl millet's growth stages exhibited similar behavior, with the later growth stages (soft dough and kernel hard) having significantly greater TDN yield than the earlier stages (boot and anthesis). 2022 cowpea had the following relationship between TDN yield and growth stage: R5

≥ R7 = R3 = R1. Sunn hemp's TDN yield increased by 88% between the R1 harvest and the end-of-season harvest. This was entirely due to an increase in forage mass, as the R1 harvest had a significantly greater TDN fraction than the end-of-season harvest (Table 3.6; Table 3.12). There were no significant differences between the forage soybean growth stages for TDN yield.

Economic returns

When comparing the economic returns of the species averaged across all growth stages at Garden City, the 2023 cowpea harvest ($1849 ha^{-1}) was the most profitable but did not differ significantly from lablab ($1565 ha^{-1}) (Figure 3.1.) When averaged across growth stages, sunn hemp (-$117 ha^{-1}) was the only species that had a negative net return. Sunn hemp was significantly less profitable than all species other than pearl millet ($365 ha^{-1}) and 2022 cowpea ($364 ha^{-1}). When comparing only the final harvest of the season, the following relationship occurred 2023 cowpea ≥ lablab = BMR forage sorghum = pearl millet = forage soybean ≥ 2022 cowpea = sunn hemp.

In Colby, a dryland environment, the economic returns were lower, but the most profitable and least profitable species were generally the same as in Garden City, an irrigated environment. Lablab ($646 ha^{-1}), cowpea ($584 ha^{-1}), and BMR forage sorghum ($459 ha^{-1}) were the most profitable species in Colby (Figure 3.1). Similar to Garden City, lablab had significantly greater economic returns than pearl millet ($195 ha^{-1}) and sunn hemp ($182 ha^{-1}). The species that showed the most difference in profitability relative to the other crops in the study, between the irrigated and dryland sites, was forage soybean. In Garden City, forage soybean profitability, averaged across harvests, was significantly less than that of only 2023 cowpea and lablab. At the end of the season, it was significantly less profitable than only 2023

cowpea. However, at Colby, forage soybeans were significantly less profitable than cowpeas and lablab and not significantly different from sunn hemp or pearl millet.

The growth stage at harvest also affected economic returns (Table 3.14). The relationship between profitability and growth stage for BMR forage sorghum was as follows: soft dough = kernel hard ≥ anthesis > boot. Pearl millet profitability increased with maturity. Pearl millet harvested at the kernel hard and soft dough stages was significantly more profitable than when harvested at anthesis and boot. In 2022, there was no significant difference in profitability between growth stages for cowpea, but the 2023 R1 harvest was at least 182% more profitable than any of the 2022 harvests. The growth stage at harvest did not have a significant effect on the profitability of sunn hemp or forage soybeans.

Discussion

The first key findings from our study are the differences in viability of the summer annual legume species, whether they were grown in irrigated or dryland locations. In the one irrigated environment (Garden City), no species faced serious establishment challenges. This result is unsurprising because water is the most significant limiting factor to agriculture in the region. With ample irrigation, alfalfa is one of the best species to grow for high yield, nutrient value, and profitability. However, under dryland conditions, alfalfa typically has low forage mass and occasional crop failure (Klocke et al., 2013). Thus, the viability of these nontraditional legume crops in the region's dryland environments is one of the first major questions that needs to be addressed.

Sunn hemp and forage soybean faced major establishment challenges. Sunn hemp failed to establish in either year at Hays (caused by a combination of drought conditions and wildlife feeding from jackrabbits [Lepus californicus] and deer [Odocoileus virginianus]), and forage

soybeans failed to establish in 2022 at Hays and were choked out by weeds at Colby in 2023. The limitations of forage soybean as a dryland crop in the region were not surprising, because dryland grain soybeans are not commonly grown in the region (USDA National Agricultural Statistics Service, 2023). It is also worth mentioning that all the legumes tested in these experiments are vulnerable to damage from herbicide drift, as evidenced by herbicide drift damage at Hays in 2023 that forced a complete replanting of the legume species in that trial. Legumes in this study are particularly susceptible to dicamba [3,6-dichloro-2-methoxybenzoic acid] and 2,4-D [2,4-Dichlorophenoxyacetic acid] injury as these herbicides are used throughout the year for weed control during the fallow period of the region's cropping systems. Chemical weed control during the fallow period of semi-arid Great Plains cropping systems is necessary to conserve water and avoid tillage in a region where water is the most important limiting factor for agricultural productivity. Based on our study, only cowpea and lablab can confidently be considered viable summer annual legumes for the semi-arid Great Plains in dryland environments. Historical agricultural practices in the region, as well as other studies, have also shown cowpea to be a viable dryland option for the semi-arid Great Plains (USDA National Agricultural Statistics Service, 1924-1956; Ten Eyck & Call, 1908; Rao et al., 2009).

Our results supported our hypothesis that grass species would produce more forage yield than legumes. This was true in both irrigated and dryland environments and aligns with the findings of Cherney et al. (1991) (Table 3.5). Our hypothesis that grass species would have greater WUE than legume species also held true in all environments (Table 3.10). However, WUE was primarily driven by yield differences, rather than water use differences. In four of the six environments, there was no significant difference among species in terms of water use. In one of the two where it was significant (Colby 2023), there was a significant difference only between

the highest water-using species (BMR forage sorghum) and the lowest water use species (sunn hemp) (Table 3.7).

On the other hand, species had a significant effect on forage yield in all environments (Table 3.5). Because WUE is a function of forage yield and water use, the fact that species did not affect water use in most environments, but did affect yield, suggests that most of the differences in WUE among species can be attributed to differences in forage yield, rather than water use. Baral (2023) reported higher WUE for cowpea than forage soybean. While we did not see a statistically significant difference between cowpea and forage soybean WUE at any of the individual site years in which both crops were present. When averaged across all four site-years at which both species were present, cowpea had a 29.8% greater WUE than forage soybean, in line with Baral's results (Table 3.10).

The legume species we tested diverged from our expectations regarding the progression of maturity. We anticipated that each legume would reach full maturity and undergo the typical maturity stages of R1 (begin flowering), R3 (begin pod formation), R5 (begin seed formation), and R7 (begin maturity) (Fehr & Caviness, 1977). Forage soybeans were the only legume in Garden City to complete this progression before the first freeze in both years. Soybean maturity is well-studied, and commercially available soybeans are assigned highly accurate maturity groups based on the length of day required to trigger reproductive stages. Therefore, we were not surprised that the forage soybean variety we used was well-adapted to the region in terms of maturity. Cowpea progressed through its growth stages in 2022; however, for reasons that are not entirely clear, it did not progress beyond the R1 stage in 2023, despite being planted earlier and using the same variety of cowpea from the same seed supplier in both years. Cowpea can be either photoperiod-sensitive or photoperiod-insensitive, depending on the genotype (Paudel et

al., 2021). Since cowpea is not a widely used commercial crop, it is possible that differences in genotype regarding photoperiod sensitivity existed among the seeds used in 2022 and 2023. While not our original intention, this difference in photoperiod yielded interesting results, highlighting the differences between a de facto early-maturing cowpea genotype and a late-maturing cowpea genotype.

In 2023 at Garden City, cowpea matured later in the growing season; our reported cowpea forage yields were greater than those reported by Baral (2023) at Ashland Bottoms outside of Manhattan, KS, but in 2022, when we were likely growing an earlier-maturing variety of cowpea, yields were lower than those reported by Baral (2023). Manhattan has a significantly higher annual rainfall than Garden City, so our irrigated trial provided a comparable environment to that of Baral (2023) in terms of water availability. Baral (2023) reported over double the forage soybean dry matter yield as we did at our Garden City trial. This could be because Western Kansas has a much higher soil pH than Eastern Kansas, and soybeans tend to struggle in high-pH soils (Obour et al., 2016; Rogovska et al., 2007).

Sunn hemp did not mature beyond R1 at any site where it established, and lablab never progressed beyond the vegetative stage at any site where it was planted. We suspect that the lack of maturity progression in both crops was due to their photoperiod sensitivity, which required a shorter day than our environment provided before the first freeze. Sunn hemp, lablab, and cowpea are native to the tropical latitudes, so it stands to reason that each species would not have photoperiod lengths well adapted for our region without adaptive breeding efforts, which none of these three crops have had in the central Great Plains (Mosjidis et al., 2012; Stephens, 2018; Boukar et al., 2019). Both grass species proceeded through their maturity progression as expected.

Forage yield increased in all species as maturity increased, but it increased by proportionally greater amounts in the two grass species and sunn hemp than in cowpea or forage soybean. This overall increase in forage yield with maturity progression aligns with Holman et al. (2018), who found that forage sorghum dry matter yield peaked at the soft dough stage. Cherney et al. (1991) also found that grasses consistently produce greater amounts of biomass than legumes. The average increase in yield from the boot stage to kernel hard in BMR forage sorghum and pearl millet was 117% and 217% respectively (Table 3.6). For sunn hemp, the forage mass increased by 116% from R1 to the end-of-season harvest.

On the other hand, the forage mass increased from the R1 to the R7 in forage soybean and 2022 cowpea by only 18% and 55%, respectively. However, cowpea's one cutting in 2023 was 79% higher yielding than the highest-yielding cowpea cutting in 2022. This result suggests that a longer-maturing cowpea genotype, which remains in the vegetative stage over the growing season, may have more forage yield potential than a shorter-maturing genotype, which progresses all the way through its life cycle before the first freeze. This finding aligns with research on forage sorghum, which has shown that photoperiod-sensitive varieties that remain in a vegetative growth stage for longer periods during the growing season produce greater biomass (Olson et al., 2012; Erbetta et al., 2024). We were unable to track lablab's yield progression through the developmental stages because it never entered a reproductive stage.

One potential explanation for the varying degrees in which maturity stage impacted forage mass is that the three species where we saw significant increases in forage mass from the first harvest to the last harvest matured earlier in the growing season than cowpea or forage soybean (Table 3.3). It could be that if forage soybean and cowpea's first harvest were taken on the same day as the other three species, the yield increases from the first harvest to the final

harvest would be similar to the other three species. For this reason, along with the fact that crops like sunn hemp, lablab, and cowpea did not hit all their expected maturity benchmarks, it may make more sense in future studies to take predetermined harvests based on days since planting instead of physiological maturity. While this may make evaluating forage nutritive value more challenging because forage nutritive value is closely linked to physiological maturity, it could provide a better understanding of how forage mass evolves throughout the growing season in these legume species.

Water use followed a similar trend in relation to physiological maturity as forage mass. It increased as maturity progressed in all species, but did so more dramatically in BMR forage sorghum, pearl millet, and sunn hemp than it did in 2022 cowpea or forage soybean (Table 3.9). This result is also most likely because there was less total time between the first water use reading and the last water use reading in 2022 cowpea and forage soybean than there was in BMR forage sorghum, pearl millet, and sunn hemp (Table 3.3). This shortened time period made it appear as if the reproductive stages in cowpea and forage soybean require less water than the other crops tested in this study; however, it is more likely that these differences between species are simply a byproduct of the time between the first and last water content measurements.

BMR forage sorghum was the only crop we tested in which physiological maturity at harvest affected WUE (Table 3.11). This result suggests that for the other crops in the study, harvesting at a particular growth stage does not maximize WUE. Our results indicate that forage mass and forage nutritive values differ based on physiological maturity. However, outside of BMR forage sorghum, concerns over WUE should not play a role in the decision of when to harvest these crops.

Our results generally supported our hypothesis that grass species would have lower CP concentrations and higher fiber concentrations than legume species (Table 3.12). However, on a per-area basis, BMR forage sorghum either outperformed or was statistically similar to all legume crops in the study in terms of CP yield. (Table 3.13). This was true for pearl millet as well, except when compared to lablab, which had a significantly greater CP yield than pearl millet. In general, the two grass crops' superior biomass production compensated for their lower CP concentrations when comparing the protein production of summer annual grass forage to summer annual legume forage on a per area basis.

Crude protein concentration declined as crops matured, but only significantly in pearl millet, 2022 cowpea, and sunn hemp (Table 3.12). This result aligns with other studies that have found a decline in CP concentration with maturity (Balde et al., 1993; Caballero et al., 2001; Rondahl et al., 2011). The decline in CP concentration between the first harvest and last harvest was larger in BMR forage sorghum, pearl millet, and sunn hemp than in forage soybean or 2022 cowpea. This relationship is the inverse of what occurred regarding forage yield, where BMR forage sorghum, pearl millet, and sunn hemp had greater increases in forage mass between the first harvest and last harvest than forage soybean and 2022 cowpea did (Table 3.6). Moyer et al. (2003) found that CP concentration and forage yield are inversely related. Our results align with those of Moyer et al. (2003), as the species that experienced the greatest forage mass gains from the first harvest to the last harvest also showed the greatest CP concentration reductions from the first harvest to the last harvest. Our reported CP concentrations for both forage soybeans and cowpeas were similar to those reported by Baral (2023) when compared at similar growth stages.

The relationship between fiber concentration and the legume species varied between ADF, NDF, and lignin concentration (Table 3.12). BMR forage sorghum and pearl millet had

greater ADF and NDF concentrations than every legume except sunn hemp, but the difference between grass species and legume species was more pronounced for NDF than ADF. Pearl millet's ADF concentration was 27%, 21%, 26%, and 29% greater than those of 2022 cowpea, 2023 cowpea, forage soybean, and lablab, respectively. BMR forage sorghum ADF concentration was not significantly greater than that of 2023 cowpea and 10%, 11%, and 13% greater than forage soybean, 2022 cowpea, and lablab ADF concentration, respectively. On the other hand, both pearl millet and BMR forage sorghum had a significantly greater NDF concentration than either year of cowpea, forage soybean, or lablab. Pearl millet had on average 59% greater NDF concentration than cowpea, forage soybean, or lablab, and BMR forage sorghum had on average 47% greater NDF concentration than the three crops. These differences stem from the differences between what ADF and NDF measure. NDF measures the entirety of a plant's fiber content: cellulose, hemicellulose, lignin, and silica, while ADF measures only the least digestible parts of the plant: cellulose, lignin, and silica (Schick, 2023). The legumes in our study all had significantly greater lignin concentration than either of the grass species in the study, so it logically follows that the NDF differences between most legume species and grass species were greater than the ADF differences because lignin has a larger overall influence on ADF concentration than it does on NDF concentration. Generally, NDF corresponds with voluntary feed intake and overall energy availability for the animal; in other words, the energy density of a forage, while ADF directly corresponds with a forage's digestibility (Schick, 2023). Based on our results, we can conclude that cowpea, lablab, and forage soybean have greater voluntary feed intake and higher concentrations of energy on a per mass basis than BMR forage sorghum or pearl millet. However, the advantage of these legumes compared to grasses in terms of digestibility is much narrower.

Our reported cowpea ADF and NDF concentrations for the R1 stage were comparable to Baral's (2023), but Baral reported much higher NDF and ADF concentrations for forage soybean at the R1 stage. We reported ADF and NDF concentrations of 27.6% and 35.1% respectively, for forage soybean at the R1 stage (Table 3.12). Baral (2023) reported ADF and NDF concentrations of 37.7% and 43.3% respectively for forage soybean.

Sunn hemp saw significant differences between R1 and end-of-season for forage nutritive measures (CP, ADF, NDF, TDN, lignin, and RFQ). For all these measures, the R1 harvest had forage nutritive values indicating higher forage quality than the end-of-season harvest, including higher CP, lower ADF, lower NDF, lower lignin concentration, higher TDN, and higher RFQ. The reason for this drastic difference in forage quality between the two harvests was that, once sunn hemp reached the R1 stage, it did not make any further advances in terms of physiological maturity. Observationally, this resulted in plant stalks becoming larger and more lignified, but, unlike other species, lignification was not offset by seed development (seeds are high in protein and starch). Because sunn hemp did not undergo seed development, its quality decreased after reaching the R1 stage. In general, sunn hemp harvested at the R1 stage had forage nutritive measures that were much more in line with those of the other legumes in the study. However, the end-of-season harvest for sunn hemp had forage nutritive measures similar to those of the grass species in the study and sometimes worse. For instance, the end-of-season harvest for sunn hemp had an RFQ value of 87, the lowest for any crop at any stage in the study. In contrast, its R1 RFQ value was roughly similar to other legumes in the study and much greater than the highest RFQ value at any stage of a grass species in the study. However, on a per area basis, sunn hemp had greater CP yields and TDN yields at end-of-season than at R1, so forage yield increases offset the decline in CP and TDN concentration between the two harvests (Table 3.13).

In a study conducted in Southeast Wyoming, another semi-arid environment, researchers reported greater CP and TDN concentrations and lower ADF and NDF concentrations for sunn hemp harvested after 60 days than for either of our two sunn hemp harvests (Eberle & Shortnacy, 2021). However, our sunn hemp forage masses were generally greater than those reported by Eberle & Shortnacy (2021), which could explain why our sunn hemp had lower forage quality.

TDN concentration and RFQ values varied across the species in this study. If ADF concentration is the measure of the portion of a forage that is low in digestibility, TDN concentration is essentially the measure of what fraction of a forage is highly digestible (Adesogan et al., 2017). BMR forage sorghum had the greatest TDN fraction (Table 3.12). The BMR trait's primary purpose is to increase the digestibility of the forage by reducing its lignin concentration (Porter et al., 1978; Cherney et al., 1986; Pedersen, 1996; Casler et al., 2003). This aligns with our results because BMR forage sorghum had the lowest lignin concentration of any of the species in the study. Forage soybean, lablab, and cowpea had the next greatest TDN fractions, while pearl millet and sunn hemp had the lowest TDN fractions (Table 3.12). This result aligns with the fact that pearl millet and sunn hemp had the greatest ADF concentration. The only two species that saw a significant effect of growth stage on TDN fraction were sunn hemp and BMR forage sorghum. In sunn hemp, the TDN fraction declined as maturity progressed. This was the result of a significant increase in ADF and lignin concentrations as sunn hemp matured. In BMR forage sorghum, the soft dough and kernel hard stages had significantly greater TDN fractions than the boot stage. This result was most likely due to an increase in starch concentration as seeds began to develop in the later growth stages.

All the legume species (excluding the end-of-season sunn hemp harvest) had significantly greater RFQ values than either pearl millet or BMR forage sorghum. This makes sense, because

RFQ is primarily based on CP, NDF, and ADF concentrations, and the legumes in this study, except for the end-of-season sunn hemp harvest, had a greater CP concentration and lower NDF and ADF concentrations than the grass species (Adesogan et al., 2017; Table 3.12). BMR forage sorghum's RFQ was significantly greater than that of pearl millet. This is most likely due to the lower ADF, NDF, and lignin concentrations of BMR forage sorghum. One promising result from this study was that all legumes in the study had RFQ values well above 100, which is the standard value for alfalfa RFQ at the full bloom stage (Adesogan et al., 2017). This fact suggests that all legumes in this study (when harvested at the proper stage, in the case of sunn hemp) produce forage of equal or superior quality to alfalfa, which significantly increases the likelihood that a producer would be willing to try one of these legume species as an alternative to alfalfa.

While not always at a significant level, RFQ generally decreased as species matured, with the notable exception of BMR forage sorghum. This trend was to be expected as quality is generally assumed to decrease with an increase in maturity (Adesogan et al., 2017; Holman et al., 2007). BMR forage sorghum RFQ peaked in the two later growth stages of soft dough and kernel hard. The most likely explanation for this is that as BMR forage sorghum matured, the starch concentration increased once it started producing seed at the soft dough and kernel hard stages. Starch is a high-energy carbohydrate that is the primary nutrient found in grain seed. While pearl millet exhibited a spike in starch concentration at the soft dough and kernel hard stages, the increase was substantially smaller than that observed in BMR forage sorghum (Table 3.12). This result suggests that there is a possibility that grain production was lower in pearl millet than it was in BMR forage sorghum. In 2022, cowpea RFQ peaked at R1, most likely due to the peak of its CP concentration. However, after dipping at R3 and R5, it rebounded at R7, likely due to seed production. In forage soybeans, starch concentrations decreased as maturity

progressed, though not at a statistically significant level. This slight decline was possibly due to the fact soybean seeds have a much higher fat and protein content and a much lower starch content than most other grain seeds (Sharma et al., 2014).

Turning to the economic returns of these species, legume seed was more expensive than grass seed (Table 3.4). This is because legume seed production is less per unit area than that of grass crops. The total seed cost per hectare was at least 58% greater for all legume species compared to the grass species, and as much as 194% greater when comparing the total seed cost of pearl millet to lablab. Lablab had seeds that were substantially more expensive than those of any other species in the study. This is likely because lablab is currently the least commonly used species within the region we tested; therefore, a lack of seed production infrastructure has likely resulted in higher seed prices. If the price of lablab seed can be reduced, it would substantially improve its profitability relative to the other species in the study (Table 3.14; Figure 3.1). The 2023 cowpea harvest was the most profitable treatment in Garden City. It was 18.1% more profitable than the 2023 lablab harvest. However, lablab seed was double the price of cowpea seed (Table 3.4). If lablab seed cost the same as cowpea seed, the 2023 cowpea harvest would only have been 9.7% more profitable than the 2023 lablab harvest. Based on the 2022 Colby trial, lablab was the most profitable species under dryland conditions. This was true despite lablab's elevated seed cost relative to the other species in the study (Figure 3.1).

Another built-in economic advantage grasses had over legumes was herbicide costs. All species received the same herbicide burndown treatment prior to planting. However, the cost of pendimethalin, used for residual weed control in legumes, versus the cost of atrazine, used for residual weed control in grasses, resulted in \$38.24 ha^{-1} greater herbicide costs for legumes compared to grasses. Commonly, a residual herbicide such as dicamba, prosulfuron

[$C_{15}H_{16}F_3N_504S$], or carfentrazone [$C_{13}H_{10}Cl_2F_3N_3O_3$] is applied ahead of sorghum or millet planting as well. However, due to the small plots used in this study and the interspecific competitiveness of grass relative to broadleaf crops, these herbicides were not applied (Holman et al., 2004; Holman et al., 2006). A production cost advantage that legumes had over grasses was the amount of nitrogen fertilizer applied. Legumes and grasses both received 56.1 kg ha^{-1} of starter 11-52-0, but the grasses received an additional 50.5 kg ha^{-1} of urea (46-0-0), resulting in an additional \$32.29 ha^{-1} in fertilizer cost for grasses. When factoring in both herbicide and fertilizer expense, grasses had a built-in \$5.95 ha^{-1} advantage over legumes before considering the crop value or seed cost differences between the species.

Lablab, cowpea, and forage soybean profit were all either statistically equivalent to or greater than both BMR forage sorghum and pearl millet in the irrigated environment at Garden City. In the dryland environment at Colby, lablab and cowpea profit was similar to BMR forage sorghum and significantly greater than pearl millet (Figure 3.2). Despite legumes having higher production costs and lower forage yields than grasses, summer annual forage legumes were economically comparable to BMR forage sorghum and millet. Legume hay was valued much higher than grass due to greater CP concentration and higher RFQ (Table 3.4; Table 3.12). Most of the legume harvests in the study produced hay valued at \$0.30 kg^{-1}. Some harvests, such as the R1 and R3 forage soybean harvests and the 2022 R1 cowpea harvest, produced hay valued at between \$0.34 and \$0.36 kg^{-1}. That is two to three times more valuable than the grass hay produced. Therefore, some legumes, namely forage soybean, lablab, and cowpea in an irrigated environment and lablab and cowpea in a dryland environment, were economically comparable or superior to grass species on a per-hectare basis. Baral (2023) reported higher profitability for forage soybean than cowpea. This was primarily due to the significantly higher yields for forage

soybeans compared to cowpeas in Baral (2023). This somewhat aligns with our results. In 2022, at Garden City, when forage soybean outyielded cowpea, it was more profitable, but in 2022, at Colby, and 2023, at Garden City, when cowpea outyielded forage soybean, the inverse was true (Table 3.14; Figure 3.1). Between legumes of similar forage quality and production costs, such as cowpea and forage soybean, forage yield was the driving factor in profitability.

The last key element of our results to discuss is how the legumes in our study compared to alfalfa. Alfalfa is the most widely grown forage legume in the semi-arid Great Plains region. Due to its high forage quality, it is highly sought after for cattle feeding and dairy operations. However, it has a large water demand and thus must generally be irrigated in the region (Klocke et al., 2013; Holman et al., 2016). To compare alfalfa to the legume species we studied, we primarily used the results of Klocke et al. (2013) and Holman et al. (2016), because they studied alfalfa in Garden City, KS, and included both irrigated and dryland treatments. The three irrigation treatments of Klocke et al. (2013) and Holman et al. (2016) most relevant to our comparisons were their fully irrigated treatment (610 mm of irrigation water applied), their partially irrigated treatment (200 mm of irrigation water applied), and their dryland treatment. We fully irrigated our legumes in the Garden City trial of our study, meaning we irrigated the crops whenever they appeared to need water. However, we applied 318 mm of irrigation in 2022 and only 102 mm in 2023, because 2022 was a dry year that required more irrigation to meet crop water demand, whereas 2023 was a wet year that required less irrigation to meet the same demand. In Klocke et al. (2013) and Holman et al. (2016), the full irrigation treatment was 610 mm applied (much higher than what we applied), because alfalfa has a longer growing season and thus higher water demand than the legumes we studied. Consequently, we found it appropriate to make comparisons to Klocke and Holman's full irrigation treatment and partial

irrigation treatment. Their full irrigation treatment parallels the management approach we took in our irrigated trials, but their partially irrigated treatment more closely aligns with the actual amount of irrigation we applied.

The first valuable comparison to make between alfalfa and the legumes in our study is forage yield. Klocke et al. (2013) report an average forage yield of 15,300 kg ha^{-1} for their fully irrigated treatment, 8,900 kg ha^{-1} for their partially irrigated treatment, and 4,300 kg ha^{-1} for their dryland treatment. None of the legumes, regardless of what growth stage they were harvested, matched the yield of Klocke et al.'s (2013) fully irrigated alfalfa treatment (Table 3.6). However, for our irrigated trials, the 2023 harvests of cowpea and lablab, as well as the end-of-season sunn hemp harvest, exceed the forage yield of alfalfa irrigated with 200 mm of water (Klocke et al., 2013). The R5 and R7 harvests of irrigated forage soybean yielded similarly to alfalfa irrigated with 200 mm of water, averaging a 7.4% yield decrease relative to the partially irrigated alfalfa. To make comparisons to dryland alfalfa, we will only discuss our 2022 Colby results, as this was our only dryland trial that was neither planted late nor faced significant establishment challenges. At Colby in 2022, cowpea, sunn hemp, and lablab all had greater forage mass than the dryland alfalfa forage mass reported in Klocke et al. (2013) (Table 3.5).

Regarding water productivity, the fully irrigated alfalfa averaged 18.2 kg ha^{-1} mm^{-1}, the partially irrigated alfalfa averaged 13.8 kg ha^{-1} mm^{-1}, and the dryland alfalfa averaged 9.6 kg ha^{-1} mm^{-1} (Klocke et al., 2013). The 2023 harvest of irrigated cowpea and lablab, as well as both the R1 and end-of-season harvest for irrigated sunn hemp, exceed the fully irrigated alfalfa's productivity (Table 3.11). All harvests of irrigated forage soybean and 2022 irrigated cowpea had roughly similar productivities to partially irrigated alfalfa. Every forage soybean harvest except the one taken at R3 exceeded the productivity of partially irrigated alfalfa. The reason the

legumes we studied outperformed alfalfa in terms of productivity was that, even when they produced lower yields than alfalfa, they used significantly less water (Klocke et al., 2013; Table 3.7). This could be partly due to the fact that alfalfa has a significantly longer growing season than the annual legumes in our study. These differences in productivity were most stark when comparing dryland alfalfa to the productivity of the dryland legumes at Colby in 2022. All species of annual legumes had greater productivity than dryland alfalfa (Table 3.10). Lablab and sunn hemp had nearly three times the productivity of dryland alfalfa, and cowpea had over twice the productivity of dryland alfalfa.

Moving to forage nutritive values, alfalfa irrigated with 610 mm of water throughout the growing season averaged a CP concentration of 21.2%; alfalfa irrigated with 200 mm of water throughout the growing season averaged a CP concentration of 23.2%; dryland alfalfa averaged a CP concentration of 22.6% (Holman et al., 2016). These CP concentrations were consistently higher than those of the legumes in our study (Table 3.12). The R1 cutting of cowpea in 2022 had a CP concentration of 21.6%, but no other legume, regardless of harvest stage, averaged a CP concentration of greater than 19.5% (the R1 cutting of sunn hemp).

Turning to the fiber measures, fully irrigated alfalfa had ADF and NDF concentrations of 31.6% and 42.2%, respectively; partially irrigated alfalfa averaged 25.6% and 36.0%, respectively; and dryland alfalfa had 24.7% and 37.0% (Holman et al., 2016). The ADF concentrations were consistently greater for the legumes in our study than the ADF concentrations of partially irrigated and dryland alfalfa (Table 3.12). Cowpea, forage soybean, and lablab had slightly lower ADF concentrations than fully irrigated alfalfa, but greater concentrations than partially irrigated and dryland alfalfa. For NDF, a slightly different trend emerged. Cowpea (37.8%), forage soybean (36.3%), and lablab (38.4%) all had lower average

NDF concentrations than fully irrigated alfalfa, but similar NDF concentrations to partially irrigated and dryland alfalfa.

For TDN concentration, fully irrigated alfalfa averaged 64.9%, partially irrigated alfalfa averaged 71.4%, and dryland alfalfa averaged 72.3% (Holman et al., 2016). These TDN concentrations were generally greater than those of our legumes, with the only legume harvest that exceeded fully irrigated TDN's concentration being R1 forage soybean (65.5%), with no other legume harvest exceeding a TDN concentration of 63.4% (R5 forage soybean) (Table 3.12). Considering the higher CP concentrations, lower fiber concentrations, and higher TDN concentrations, partially irrigated and dryland alfalfa were of higher quality than the legumes in our study. Cowpea, forage soybean, lablab, and R1 sunn hemp were similar in forage quality to fully irrigated alfalfa.

Our final comparison to alfalfa is profitability. Based on the results of Holman et al. (2016), we estimated that for alfalfa irrigated with 610 mm of water, profitability was \$2,193.19 ha^{-1}; for alfalfa irrigated with 200 mm of water, profitability was \$1,411.81 ha^{-1}; for dryland alfalfa, profitability was \$66.24 ha^{-1}. Fully irrigated alfalfa was more profitable than any of the legumes in our study, regardless of harvest stage (Table 3.14). However, the desire to conserve irrigation water may lead more producers to transition to reduced irrigation regimens. The legumes in our study required a similar amount of irrigation water to fully irrigate them, as did the partially irrigated alfalfa treatment from Holman et al. (2016). The 2023 irrigated cowpea and lablab harvests exceeded the profitability of partially irrigated alfalfa (Table 3.14). The summer annual legumes we tested under dryland conditions had greater profitability than dryland alfalfa (Figure 3.1). Dryland cowpea and lablab both had around 9 times the profitability of dryland

alfalfa. This was primarily because dryland alfalfa had much lower yields than the summer annual legumes at our 2022 Colby trial (the basis for our dryland profitability estimates).

Conclusion

This study supported our hypotheses that summer annual grasses would have higher forage yields and productivity than summer annual legumes, but that summer annual legumes would have higher CP concentration and greater digestibility. We were also able to identify summer annual legume species that can serve as viable alternatives to alfalfa in the region. When receiving similar amounts of irrigation water, forage soybeans, cowpeas, and lablab all displayed potential as alternatives to alfalfa due to their forage yield, nutritive value, and economic profitability that was similar to or surpassed that of alfalfa. In dryland environments, lablab and cowpea showed the most promise, with much higher yields and profitability than dryland alfalfa. We would not recommend growing either forage soybean or sunn hemp in dryland environments across the semi-arid Great Plains due to both establishment challenges and low economic profitability. We also caution against growing sunn hemp under irrigation for forage purposes because it had negative net economic returns even under irrigation.

This study provided strong evidence that further investigation is warranted into summer annual legume forage in the semi-arid Great Plains, particularly cowpea and lablab. These species could provide higher profits, greater yields, increased cropping flexibility, and improved yield stability compared to dryland alfalfa. Further areas of investigation for these two species include 1) tracking the impact of forage nutritive value and forage yield based on growing degree days as opposed to physiological growth stage, and 2) exploring the impact that using early- vs. late-maturing genotypes has on forage yield, nutritive value, water use, and profit. These results

support our hypothesis that summer annual legumes can be grown to help meet the region's demand for high-quality forage.

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Figures

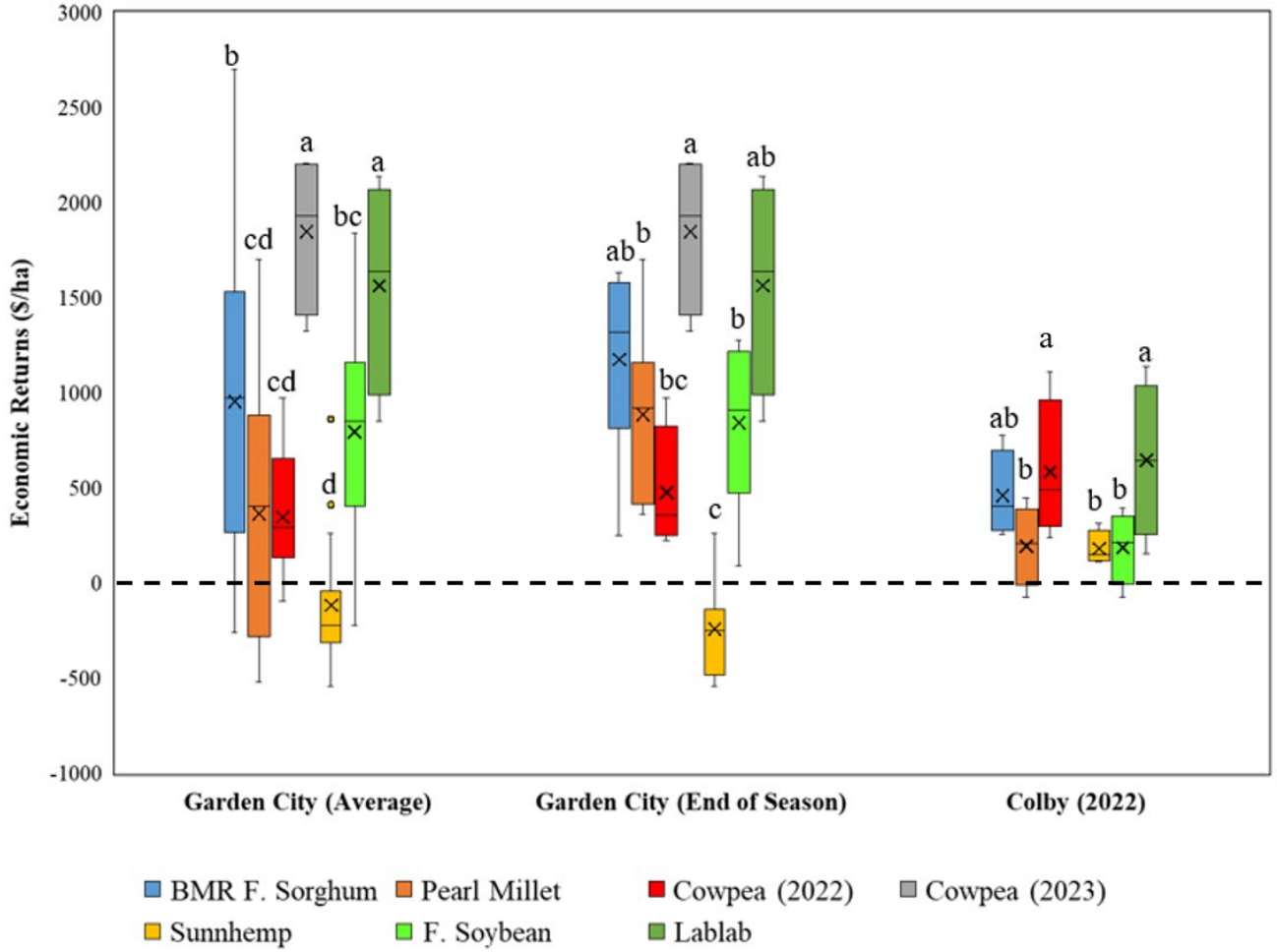

Figure 3.1. Economic return ($/ha) in Garden City, KS averaged across all growth stages and for the end of season harvest of 2022-23 and end of season for Colby, KS in 2022. Garden City cowpea harvest is separated between 2022 and 2023 because of significant differences in cowpea maturity progression between the two years. Means with the same letter are not significantly different (α =0.05) among species within a group. In each box, X indicates the mean, and the horizontal bar indicates the median.

Tables

Table 3.1. Monthly precipitation in 2022, 2023, and the 60-yr averages (1924-2024) for Garden City, Colby, and Hays, KS. (Kansas State University, 2024; National Oceanic and Atmospheric Administration, 2024).

	Garden City			Colby			Hays		
Month	**2022**	**2023**	**60-yr ave.**	**2022**	**2023**	**60-yr ave.**	**2022**	**2023**	**60-yr ave.**
	mm								
Jan.	12	3	11	7	13	9	5	23	13
Feb.	0	15	13	1	16	12	0	7	17
Mar.	7	1	29	14	11	26	31	6	40
Apr.	10	57	40	16	19	45	11	18	52
May	55	111	78	67	146	85	86	79	84
Jun.	32	130	74	28	113	70	36	81	80
Jul.	54	97	73	98	93	88	45	57	91
Aug.	10	54	64	43	47	63	35	95	78
Sept.	15	47	37	16	0	37	54	17	51
Oct.	1	21	29	12	14	33	4	19	39
Nov.	3	5	16	0	6	16	6	11	24
Dec.	1	38	14	9	18	11	17	45	18
Annual	199	578	477	310	497	495	329	459	585

Table 3.2. Planting date, harvest date, plant available water (PAW) at planting, and in-season water for summer annual forages in Garden City, Colby, and Hays, KS 2022-23.

Location	Year	Planting date	Harvest date	PAW at planting[a]	In-season water[b]
				mm	
Garden City	2022 (grasses)	17-Jun	6-Oct	142	426
	2022 (legumes)	17-Jun	11-Oct/14-Oct	142	426
	2023 (grasses)	30-May	14-Sep	202	366
	2023 (legumes)	30-May	4-Oct/10-Oct	202	446
Colby	2022	15-Jul	14-Oct	95	149
	2023	31-Jul	10-Oct	147	55
Hays	2022	23-Jun	12-Oct	208	137
	2023 (grasses)	21-Jun	2-Oct	87	203
	2023 (legumes)[c]	20-Jul	2-Oct	87	125

[a]Average across all plots

[b]In-season water is the sum of precipitation and irrigation between planting and harvest (at GC precipitation values include all precipitation from planting to final harvest of a given species during the growing season)

[c]Legumes in the 2023 Hays trial had to be replanted due to herbicide damage

Table 3.3. Harvest dates of summer annual forages by stage and species in Garden City, KS 2022-23.

Year	Growth Stage at Harvest	BMR Forage Sorghum	Pearl Millet	Cowpea	Sunn hemp	Forage Soybean	Lablab
2022	Boot/R1	22-Aug	8-Aug	14-Sep	30-Aug	14-Sep	—
	Anthesis/R3	30-Aug	15-Aug	6-Oct	—	26-Sep	—
	Soft Dough/R5	26-Sep	8-Sep	11-Oct	—	6-Oct	—
	Kernel Hard/R7	6-Oct	6-Oct	14-Oct	—	11-Oct	—
	End of Season	—	—	—	11-Oct	—	—
2023	Boot/R1	27-Jul	20-Jul	4-Oct	27-Jul	14-Sep	—
	Anthesis/R3	14-Aug	9-Aug	—	—	19-Sep	—
	Soft Dough/R5	29-Aug	25-Aug	—	—	27-Sep	—
	Kernel Hard/R7	14-Sep	14-Sep	—	—	10-Oct	—
	End of Season	—	—	—	10-Oct	—	10-Oct

Table 3.4. Values used to estimate cost of production and market value of forage

Production Costs	Unit	Value
Drilling[a]	$ ha^{-1}	41.88
Seeding Rate	kg ha^{-1}	
BMR Forage Sorghum		16.8
Pearl Millet		13.5
Forage Soybean		44.8
Cowpea		44.8
Sunn Hemp		44.8
Lablab		44.8
Seed Cost	$ kg^{-1}	
BMR Forage Sorghum[b]		3.74
Pearl Millet[c]		4.18
Forage Soybean[d]		3.89
Cowpea[b]		2.75
Sunn hemp[b]		4.18
Lablab[e]		5.5
Swathing[a]	$ ha^{-1}	36.82
Baling[af]	$ bale^{-1}	14.76
Stacking[a]	$ bale^{-1}	5
Glyphosate[g]	$ L^{-1}	14.54

Glyphosate rate	L ha^{-1}	4.68
2,4-D[g]	$ L^{-1}	6.09
2,4-D rate	L ha^{-1}	1.17
Dicamba[g]	$ L^{-1}	23.33
Dicamba rate	L ha^{-1}	1.75
Atrazine[g]	$ L^{-1}	5.76
Atrazine rate	L ha^{-1}	4.67
Prowl[g]	$ L^{-1}	14.74
Prowl rate	L ha^{-1}	2.34
Herbicide application[a]	$ ha^{-1}	19.57
Number of applications		
Grasses		1
Legumes		2
MAP (11-52-0)[h]	$ kg^{-1}	0.88
MAP rate	kg ha^{-1}	56.05
Urea[h]	$ kg^{-1}	0.64
Urea rate (grasses only)	kg ha^{-1}	50.45
Fertilizer application[a]	$ ha^{-1}	16.09
Land rental	$ ha^{-1}	
Garden City[i]		462.08
Colby[j]		148.26

Irrigation[k]	$ ha^{-1}	126.74
Crop Value (hay type)[l]	$ kg^{-1}	
Supreme Legume (RFQ ≥ 185)		0.394
Premium Legume (RFQ 170-184)		0.374
Good Legume (RFQ 150-169)		0.25
Utility Legume (RFQ < 130)		0.121
Grass (Sudan Good)		0.121

[a](AgManager, 2022)
[b](Green Cover, 2024)
[c](Albert Lea Seed, 2024)
[d](Merit Seed, 2024)
[e](Browning Seed, 2024)
[f]Bale size of approximately 519 kg of dry matter
[g](Lancaster et al., 2024)
[h](Ibendahl et al., 2023b)
[i](Ibendahl & O'Brien, 2023a)
[j](Ibendahl & O'Brien, 2023b)
[k](Ibendahl et al, 2023a)
[l]Average of hay price from Kansas direct hay reports 2/13/24-3/26/24 (USDA Agricultural Marketing Service, 2022-23)

Table 3.5. Forage yield of summer annual legumes final cuttings by location and year and results of Type III Test of Fixed Effects. Garden City, Colby, and Hays, KS 2022-23.

	Location and Year					
	Garden City (Irrigated)		**Colby (Dryland)**		**Hays (Dryland)**	
Species	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**
	kg ha^{-1}					
BMR Forage Sorghum	21641 a[a]	29847 a	11818 a	6704 a	5960 a	3348 a
Pearl Millet	23665 a	21040 b	8556 ab	5119 ab	2420 b	2741 a
Cowpea	6479 b	12366 c	5038 c	2479 b	3828 b	1024 b
Sunn Hemp	11037 b	9664 c	5288 c	1838 b	——	——
Forage Soybean	7232 b	9282 c	3553 c	——	——	805 b
Lablab	——	11668 c	5832 bc	3248 b	——	1408 b
Fixed Effects	**All Locations**	**Dryland Locations**	**Garden City**	**Colby**	**Hays**	
	P>F					
Species	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	
Year	0.1117	<0.0001	0.0781	0.0061	0.0037	
Location	<0.0001	0.0011	——	——	——	
Species x Year	0.2467	0.0621	0.0288	0.2531	0.0003	
Species x Location	<0.0001	0.0007	——	——	——	
Year x Location	0.0007	0.0037	——	——	——	
Species x Year x Location	0.0002	0.0483	——	——	——	

[a]Means within a column followed by the same letter are not significantly different (α =0.05) among species within a year and location

Table 3.6. Forage yield of summer annual forages by growth stage at harvest and year. Type III test of fixed effects for impact of growth stage at harvest on forage yield at Garden City, KS 2022-23.

	Species and year(s)							
	BMR F. Sorghum[a]	Pearl Millet		Cowpea		Lablab	Sunn hemp	F. Soybean
Growth stage at harvest	2022-23	2022	2023	2022	2023	2023	2022-23	2022-23
	kg ha^{-1}							
Boot/R1	11869 b[b]	8014 b	6189 b	4171 b	12366	——	4929 b	7022
Anthesis/R3	22999 ab	7989 b	16749 a	5185 ab	——	——	——	6490
Soft Dough/R5	31721 a	19597 a	22868 a	6900 a	——	——	——	8224
Kernel Hard/R7	25744 a	23665 a	21041 a	6479 ab	——	——	——	8257
End of Season	——	——	——	——	——	11668	10350 a	——

Fixed Effects	All Species	BMR F. Sorghum	Pearl Millet	Cowpea[c]	Sunn hemp	F. Soybean
	P>F					
Growth stage at harvest	<0.0001	0.0018	0.0001	0.0322	0.0014	0.3347
Year	0.1211	0.4048	0.2404	——	0.3116	0.0024
Species	<0.0001	——	——	——	——	——
Growth stage x Year	0.3229	0.1912	0.0446	——	0.4759	0.5400
Growth stage x Species	<0.0001	——	——	——	——	——
Year x Species	0.3035	——	——	——	——	——
Growth stage x Year x Species	0.0166	——	——	——	——	——

[a]F. is short for forage whenever used
[b]Means within a column followed by the same letter are not significantly different (α =0.05) among growth stage at harvest. If no letters are present in a column there were no significant differences within that column.
[c]Only the 2022 harvests for cowpea were statistically analyzed because in 2023 cowpea only reached the R1 stage prior to the end of the growing season.

Table 3.7. Water use of summer annual forages in Garden City, Colby, and Hays KS 2022-23 and results of type III test of fixed effects.

	Location and Year					
	Garden City		Colby		Hays	
Species	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**
	mm					
BMR Forage Sorghum	455	467 c[a]	220	173 a	271	200
Pearl Millet	485	439 c	222	163 a	240	182
Cowpea	453	533 abc	213	143 ab	289	198
Sunn Hemp	408	586 ab	179	121 b	—	—
Forage Soybean	476	620 a	228	—	—	191
Lablab	—	518 bc	179	148 ab	—	183
Mean	455 B[b]	527 A	211 A	153 B	266 A	191 B
Fixed Effects	**All Locations**	**Dryland Locations**	**Garden City**	**Colby**	**Hays**	
	P>F					
Species	0.0187	0.0034	0.01	0.0018	0.1725	
Year	0.4949	0.0006	0.0028	0.002	0.0339	
Location	<0.0001	0.0151	—	—	—	
Species x Year	0.0003	0.6502	0.0004	0.851	0.44	
Species x Location	0.0003	0.0435	—	—	—	
Year x Location	0.0004	0.6425	—	—	—	
Species x Year x Location	0.0004	0.6957	—	—	—	

[a]Means within a column followed by the same lower-case letter are not significantly different (α =0.05) among species within a year and location. If no letters are present that indictates no significant difference among species.

[b]Means within a location followed by a different upper-case letter are significantly different (α =0.05) between years.

Table 3.8. Pearson correlation coefficients among forage mass, water use, water use efficiency, water availability[a], and crop type[b] across all trials (n=113).[c]

	Forage Mass	Water Use	Water Use Efficiency	Water Availability
Water Use	**0.6174**			
Water Use Efficiency	**0.6408**	0.0948		
Water Availability	**0.6294**	**0.9593**	0.1322	
Crop Type	**-0.4001**	0.0904	**-0.6318**	0.0456

[a]Water availablity is plant available water at planting added to in-season precipitation and irrigation.

[b]For the purposes of this correlation analysis, crop type refers to legumes vs. Grasses. Legumes were assigned a value of 1 and grasses a value of 0, so positive R^2 values indicate a variable's positive correlation with legumes crops, and negative R^2 values indicate a positive correlation with grass crops.

[c]Values in bold are statistically significant (α =0.05).

Table 3.9. Water use of summer annual legumes by growth stage at harvest and year in Garden City, KS 2022-23 and results of type III test of fixed effects.

		Species				
Year	**Growth Stage at Harvest**	**BMR F. Sorghum**	**Pearl Millet**	**Cowpea**	**Sunn hemp**	**F. Soybean**
		mm				
2022	Boot/R1	226 d[a]	179 c	338 c	243 b	357 c
	Anthesis/R3	261 c	234 c	438 b	—	411 b
	Soft Dough/R5	385 b	355 b	445 ab	—	468 a
	Kernel Hard/R7	455 a	486 a	453 a	—	476 a
	End of Season	—	—	—	407 a	—
	Mean	332 B[b]	314	419	325	428 B
2023	Boot/R1	285 c	174 c	533	281 b	495 d
	Anthesis/R3	373 b	333 b	—	—	548 c
	Soft Dough/R5	430 a	443 a	—	—	579 b
	Kernel Hard/R7	467 a	439 a	—	—	620 a
	End of Season	—	—	—	586 a	—
	Mean	389 A	347	533	434	560 A
Fixed Effects	**All Species**	**BMR F. Sorghum**	**Pearl Millet**	**Cowpea[c]**	**Sunn hemp**	**F. Soybean**
	P>F					
Growth stage at harvest	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0003
Year	0.0007	0.0159	0.2766	—	0.0712	0.0049
Species	<0.0001	—	—	—	—	—

Growth stage x Year	0.0006	0.0003	<0.0001	—	0.0011	0.0247
Growth stage x Species	<0.0001	—	—	—	—	—
Year x Species	<0.0001	—	—	—	—	—
Growth stage x Year x Species	0.0355	—	—	—	—	—

[a]Means within a column followed by the same lower-case letter are not significantly different (α =0.05) among cutting stages at harvest within a species and year.

[b]Means within a species followed by a different upper-case letter are significantly different (α =0.05) between years.

[c]Only the 2022 harvests for cowpea were statistically analyzed because in 2023 cowpea only reached the R1 stage prior to the end of the growing season.

Table 3.10. Water use efficiency of summer annual legumes by location and year and results of type III test of fixed effects. Garden City, Colby, and Hays, KS 2022-23.

	Location and Year					
	Garden City		Colby		Hays	
Species	2022	2023	2022	2023	2022	2023
	kg ha^{-1} mm^{-1}					
BMR Forage Sorghum	47.2 a	64.1 a	53.4 a	38.5 a	22.9 a	15.9 a
Pearl Millet	48.6 a	47.1 b	35.2 b	31.5 ab	10.4 b	15.4 a
Cowpea	14.2 b	23.1 c	23.3 bc	16.9 b	13.6 b	5.1 b
Sunn hemp	26.4 b	16.4 c	30.4 bc	17.6 b	—	—
Forage Soybean	15.2 b	15.0 c	15.9 c	—	—	4.5 b
Lablab	—	22.4 c	28.7 bc	22.2 ab	—	8.2 ab

Fixed Effects	All Locations	Dryland Locations	Garden City	Colby	Hays
	P>F				
Species	<0.0001	<0.0001	<0.0001	<0.0001	0.0002
Year	0.0282	0.0095	0.2373	0.0289	0.2149
Location	<0.0001	<.0001	—	—	—
Species x Year	0.1114	0.131	0.0061	0.5765	0.0018
Species x Location	<0.0001	0.0124	—	—	—
Year x Location	0.0085	0.3096	—	—	—
Species x Year x Location	0.0061	0.436	—	—	—

[a]Means within a column followed by the same lower-case letter are not significantly different (α =0.05) among species within a year and location.
[b]Means within a location followed by a different upper-case letter are significantly different (α =0.05) between years.

Table 3.11. Water use efficiency of summer annual legumes by growth stage at harvest and year and results of Type III test of fixed effects in Garden City, KS 2022-23.

	Species and year(s)							
	BMR F. sorghum[a]		Pearl millet	Cowpea		Sunn hemp	F. Soybean	Lablab
Growth Stage at Harvest	2022	2023	2022-23	2022	2023	2022-23	2022-23	2023
	kg ha^{-1} mm^{-1}							
Boot/R1	59.7 ab[b]	36.5 b	42.5	12.5	23.1	19.5	16.4	—
Anthesis/R3	87.2 a	61.8 a	42.6	11.8	—	—	13.5	—
Soft dough/R5	82.5 a	75.3 a	54.3	15.6	—	—	15.8	—
Kernel hard/R7	47.4 b	64.3 a	48.0	14.2	—	—	15.2	—
End of season	—	—	—	—	—	21.5	—	22.4

Fixed Effects	All species	BMR F. sorghum	Pearl millet	Cowpea[c]	Sunn hemp	F. soybean
	P>F					
Growth stage at harvest	0.0003	0.0482	0.6783	0.2683	0.4027	0.6903
Year	0.1862	0.1818	0.9616	—	0.0302	0.3585
Species	<0.0001	—	—	—	—	—
Growth stage x Year	0.1227	0.0135	0.2479	—	0.3280	0.4399
Growth stage x Species	0.0002	—	—	—	—	—
Year x Species	0.0870	—	—	—	—	—
Growth stage x Year x Species	0.0059	—	—	—	—	—

[a]F. is short for forage whenever used
[b]Means within a column followed by the same letter are not significantly different (α =0.05)
among growth stage at harvest.
[c]Only the 2022 harvests for cowpea were statistically analyzed because in 2023 cowpea only reached the R1 stage prior to the end of the growing season.

Table 3.12. Forage nutritive value of summer annual legumes species in Garden City, KS by species and growth stage at harvest across the years 2022 and 2023.

Treatment	Growth Stage at Harvest	CP	Starch	ADF	NDF	Lignin	TDN	RFQ
		%						
BMR Forage Sorghum	Boot	11.27	4.33 b	33.57	53.80	2.96	63.56 b	119
	Anthesis	8.09	4.94 b	34.88	59.10	2.68	64.58 ab	107
	Soft dough	7.00	9.06 a	31.07	52.64	2.18	68.00 a	128
	Kernel hard	6.26	9.04 a	31.22	50.70	2.24	67.67 a	131
	Mean	8.15 C	6.84 B	32.69 B	54.06 B	2.52 D	65.95 A	120 C
Pearl Millet	Boot	16.51 a	3.22 b	34.57 b	54.47 b	3.36 c	59.23	106 a
	Anthesis	11.67 b	3.61 ab	37.51 ab	59.62 a	4.07 bc	58.75	96 ab
	Soft dough	8.69 c	5.43 a	37.69 ab	58.88 ab	4.41 ab	60.24	100 ab
	Kernel hard	7.68 c	4.87 ab	39.59 a	61.39 a	4.95 a	58.44	94 b
	Mean	11.13 B	4.19 C	37.42 A	58.62 A	4.23 C	59.04 C	98 D
Cowpea	2022 R1	21.58 a	4.83 b	27.5	33.31	6.23	61.72	186
	2022 R3	17.19 ab	6.09 b	30.82	38.32	6.46	61.49	158
	2022 R5	14.42 b	8.37 a	30.45	38.90	6.16	61.98	159
	2022 R7	15.21 b	8.51 a	28.81	36.70	5.87	63.15	170
	2022 Mean	17.10 A	6.95 B	29.39 C	36.80 D	6.18 B	62.08 B	168 AB
	2023 R1	14.83 AB	8.43 A	30.83 BC	38.73 D	6.28 B	61.56 B	155 B
Sunn Hemp	R1	19.49 a	4.16 b	34.24 b	39.70 b	7.21 b	59.92 a	155 a
	End of season (R2)	9.54 b	5.05 a	48.01 a	58.63 a	11.25 a	51.49 b	87 b
	Mean	12.89 B	4.61 C	40.74 A	48.62 C	9.26 A	56.47 D	122 C
Forage Soybean	R1	17.29	5.81	27.58	35.12	5.63	65.48	185
	R3	18.46	5.03	29.18	34.87	6.38	63.25	180
	R5	15.87	4.52	30.80	37.56	7.14	63.41	166
	R7	13.59	4.24	30.95	37.72	7.88	62.97	164
	Mean	16.30 A	4.90 C	29.63 C	36.31 D	6.76 B	63.78 B	174 A
Lablab	End of season (vegetative)	17.22 A	3.94 C	28.93 C	35.60 D	6.10 B	63.36 B	176 A

Test of fixed effects	CP	Starch	ADF	NDF	Lignin	TDN	RFQ
				P>F			
Species	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Growth stage at harvest	<0.0001	0.0001	0.0097	0.0255	0.0228	0.1338	0.0592
Species x Growth stage	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0004

[a]Means followed by the same lower-case letter within a column within a species are not significantly difference (α =0.05)

[b]Species means followed by the same upper-case letter within a column are significantly different (α =0.05).

Table 3.13. CP yield and TDN yield for summer annual forage species in Garden City, KS by species and growth stage across the years 2022 and 2023.

Species	Growth stage at harvest	CP Yield	TDN Yield
		kg ha^{-1}	
BMR forage sorghum	Boot	1360	7555 b
	Anthesis	1881	14855 ab
	Soft dough	2210	21589 a
	Kernel hard	1600	17412 a
	Mean	1763 AB[b]	15353 A
Pearl millet	Boot	1147 b[a]	4112 b
	Anthesis	1446 ab	7590 b
	Soft dough	1865 a	12882 a
	Kernel hard	1714 ab	12997 a
	Mean	1547 B	9395 B
Cowpea	2022 R1	898	2572 b
	2022 R3	899	3200 ab
	2022 R5	1002	4268 a
	2022 R7	999	4095 ab
	2022 Mean	949 C	3534 D
	2023 R1	1810 AB	7616 BC
Sunn hemp	R1	877	2801 b
	End of season (R2)	1008	5277 a

	Mean	943 C	4039 D
Forage Soybean	R1	1134	4600
	R3	1213	4130
	R5	1328	5214
	R7	1131	5196
	Mean	1201 C	4785 CD
Lablab	End of season (vegetative)	2027 A	7431 BC

Test of fixed effects	**CP Yield**	**TDN Yield**
	P>F	
Growth stage at harvest	0.5997	0.0044
Species	<0.0001	<0.0001
Growth stage x Species	0.3884	<0.0001

[a]Means followed by the same lower-case letter within a column within a species are not significantly difference (α =0.05)
[b]Species means followed by the same upper-case letter within a column are significantly different (α =0.05).

Table 3.14. Economic return of irrigated summer annual forages in Garden City, KS by species and growth stage at harvest across the years 2022-23.

	Treatment					
Growth stage at harvest	**BMR F. Sorghum**	**Pearl Millet**	**Cowpea**	**Sunn hemp**	**F. Soybean**	**Lablab**
	$ ha^{-1}					
Boot/R1	22.95 ef	–392.02 f	217.43 cdef	–4.55 ef	924.42 abc	—
Anthesis/R3	948.47 abc	108.90 def	234.14 cdef	—	579.43 bcde	—
Soft Dough/R5	1673.82 a	813.41 bcd	633.81 bcde	—	834.50 bcd	—
Kernel Hard/R7	1176.74 ab	871.53 bcd	535.64 cdef	—	842.26 bcd	—
2023 R1	—	—	1789.86 a	—	—	—
End of Season	—	—	—	–256.06 ef	—	1506.47 ab
Test of Fixed Effects	**All Species**	**BMR F. Sorghum**	**Pearl Millet**	**Cowpea**	**Sunn hemp**	**F. Soybean**
	P>F					
Growth stage at harvest	<0.0001	0.0023	<0.0001	0.0126	0.0677	0.5475
Species	<0.0001	—	—	—	—	—
Growth stage x Species	<0.0001	—	—	—	—	—

[a]Means followed by the same letter are not significantly different (α =0.05).

Chapter 4 - Impact of seeding rate on warm-season annual forage grasses in the semi-arid Great Plains

Abstract

The semi-arid Great Plains region is highly suitable for livestock production, with a large concentration of beef cattle and a growing number of dairy cattle. The region, which stretches north to south from the prairie provinces of Canada to the plains of Texas, is also experiencing declining aquifers for irrigation. This decline creates the need for water-efficient forage-based cropping systems. Warm season annual forage grasses, such as forage sorghum [*Sorghum bicolor (L.) Moench*], sudangrass [*Sorghum bicolor var. Sudanese*], sorghum-sudan [*Sorghum bicolor x S. bicolor var. Sudanese*], and pearl millet [*Pennisetum glaucum*], can play a critical role in these forage-based cropping systems as well as mixed grain-forage systems. The purpose of this study was to test the effect of changing the seeding rate of these grasses on forage yield, establishment rate, biophysical traits, forage nutritive quality, and profitability. During the years 2022 and 2023, we conducted four trials (two irrigated and two dryland) at Garden City, KS, and Hays, KS, where the above-listed species were planted at six different seeding rates, starting at 370,000 seeds ha^{-1} and increasing by increments of 370,000 seeds ha^{-1} to 2,220,000 seeds ha^{-1}. In 2024, at Garden City, KS, and Hays, KS, three additional trials (one irrigated and two dryland) were conducted for forage sorghum, which included seven seeding rates: 0.37 M, 0.74 M, 1.48 M, 2.22 M, 2.96 M, 3.7 M, and 4.44 M seeds ha^{-1}. Our results indicate that the seeding rate generally has a positive correlation with forage yield, with significant variation depending on the species and environment. We also established negative correlations between seeding rate and plant height, tillers per plant, stalk diameter, crude protein concentration, and lignin

concentration. Profitability varied greatly by species, seeding rate, and environment, with pearl millet consistently trailing the other three species due to generally lower yields.

Core ideas

- All species in the study exhibited initial increases in forage mass as the seeding rate increased, but generally reached a seeding rate at which forage mass gains would plateau. There were two exceptions to this trend. First, forage sorghum under irrigated conditions did not exhibit the same clear plateau relationship, but instead appeared to continue yielding gains up to the highest seeding rate tested. Second, under the driest conditions, there was no statistically significant increase in forage mass as the seeding rate increased for any species.
- When the seeding rate increased, plant height, tillering, and stalk diameter tended to decrease. This relationship was generally true for every species in the study.
- We did not find a clear relationship between seeding rate and any of the forage nutritive values analyzed. This was true for every species in the study.
- In irrigated and high precipitation dryland environments, crude protein (CP) yield and total digestible nutrient (TDN) yield generally increased as the seeding rate increased; however, in the driest environment, the seeding rate did not have a significant effect on CP or TDN yield.
- Generally, increased plant height and stalk diameter were indicators of reduced forage quality, while an increased leaf-to-stem ratio and number of tillers typically indicated increased forage quality.
- The economic optimum seeding rate varied significantly depending on species and the growing environment. However, it was typically lower in drier environments.
- Pearl millet was generally the lowest yielding and least profitable species grown.

Introduction

The semi-arid Great Plains region is home to the largest concentration of confined feedlots in the country, as well as a growing number of confined dairies (Drouillard, 2018; Federal Milk Marketing Order 126, 2017). Meeting the demands of these industries is one of the driving forces behind the cropping systems of the region (Drouillard, 2018; Guerrero et al., 2012). While some research suggests it could prove economically viable to transport grain into the region for cattle feeding purposes, it is not economically practical to ship forage over long distances due to its bulkiness and low nutrient density relative to grain. Hence, there will remain an economic demand for locally grown forage by the region's livestock feeding industry (Clary et al., 1986).

Along with the economic demand for locally sourced forage production, forage crops are an ideal fit for water-limited, semi-arid Great Plains cropping systems because they are more water-use-efficient and resilient than grain or oilseed crops (Nielsen et al., 2006). Without adequate water at or near the reproductive and grain-filling growth stages, grain and oilseed crops risk significant yield loss (Nielsen et al., 1996, 2005). Forage yields, on the other hand, are more dependent on vegetative biomass than grain development and are thus better positioned to maximize the use of rainfall received throughout the entire growing season, resulting in greater productivity and resilience, a major advantage in a region where rainfall is often infrequent and unpredictable.

Among annual forage crops, warm-season grasses tend to have the highest water use efficiency due to their high biomass production (National Drought Mitigation Center, 2024; Bhattarai et al., 2019). Some of the main warm-season forage grasses grown in the region are forage sorghum [*Sorghum bicolor (L.) Moench*], sudangrass [*Sorghum bicolor var. Sudanese*],

sorghum-sudan [*Sorghum bicolor x S. bicolor var. Sudanese*], and pearl millet [*Pennisetum glaucum*]. Forage sorghum originated in the heart of Africa (modern-day Ethiopia and Sudan) (Bhattarai et al., 2019). Due to its origin in a semi-arid climate, it is a heat and drought-tolerant crop that is well adapted to semi-arid regions worldwide. It is a morphologically diverse species that includes many varieties. Forage sorghum will grow in soils of moderate fertility and grows best in soils of pH 6-7. It is not particularly tolerant of acidic or calcareous soils but performs better on heavier and wetter soils than pearl millet (Hanna & Sollenberger, 2007). When drilled in narrow rows, the current K-State Extension seeding rate recommendation is 11-22 kg ha^{-1}(Roozeboom et al., 2008). Using the seed weight of the forage sorghum variety grown in our study, this converts to a recommended rate of between 0.573 M seeds ha^{-1} and 1.146 M seeds ha^{-1} (Table 4.1). Forage sorghum generally grows between 6 and 12 ft. tall (Bhattarai et al., 2019). It uses significantly less fertilizer and water than corn [*Zea mays* L.] but is highly responsive to N fertilization (Newman et al., 2013; Holman et al., 2019). However, sorghum silage is less energy-dense than corn silage (Bhattarai et al., 2019). In 2022, Texas (2.6 million tons on 175,000 acres) and Kansas (788,000 tons on 105,000 acres) were the highest sorghum silage-producing states (USDA-NASS, 2023).

Sudangrass is technically a subspecies of sorghum but is treated as a distinct species because of its different growth habits and panicle structure (Bhattarai et al., 2019). Sudangrass tillers more than forage sorghum, has thinner stalks and narrower leaf blades, and can regrow more rapidly (Pedersen & Rooney, 2004). Sudangrass is primarily used for grazing and hay (Pedersen & Rooney, 2004; Roozeboom et al., 2008). When drilled in narrow rows, the current K-State Extension seeding rate recommendation for sudangrass under dryland conditions in western Kansas is 11-17 kg ha^{-1} and 34 kg ha^{-1} under irrigated conditions (Roozeboom et al.,

2008). Using the seed weight of the sudangrass variety grown in our study, this converts to a recommended rate of between 0.696 and 1.076 M seeds ha^{-1} under dryland conditions and a recommended rate of 2.152 M seeds ha^{-1} under irrigated conditions (Table 4.1).

Sudangrass easily hybridizes with forage sorghum to create sorghum-sudan (Bhattarai et al., 2019). These hybrids act as an intermediary between the two, with the tall, thick stalks of forage sorghum and the leafiness and tillering potential of sudangrass. Producers use sorghum-sudan for silage, hay, or grazing (Pedersen & Rooney, 2004; Undersander, 2003). Like forage sorghum and sudangrass, sorghum-sudan works very well as a cover crop because of its ability to quickly add organic matter to worn-out soils as well as suppress weeds and nematodes (Sustainable Agriculture Research and Education, 2007). When drilled in narrow rows, the current K-State Extension seeding rate recommendation for sorghum-sudan under dryland conditions in western Kansas is 11-17 kg $ha^{-1,}$ and under irrigated conditions, it is 34 kg ha^{-1} (Roozeboom et al., 2008). Using the seed weight of the sorghum-sudan variety grown in our study, this converts to a recommended rate of between 0.56 and 0.866 M seeds ha^{-1} under dryland conditions and a recommended rate of 1.731 M seeds ha^{-1} under irrigated conditions (Table 4.1).

Pearl millet is a morphologically diverse species that originated in northern Africa. It can grow up to 5 m tall, but most cultivars grow to 2-3 m in height (Hanna & Sollenberger, 2007). Pearl millet is well suited to the semi-arid Great Plains because it thrives between 77-95 ºF (Marsalis, 2012). However, it is sensitive to cold early in the growing season (Marsalis, 2012). Pearl millet is also known for its productivity even in soils with low nutrient and moisture content, as well as its higher tillering potential and leafiness (Kumar, 1989; Singh et al., 2017; Marsalis, 2012). It grows best on well-drained loamy or sandy soils (Hanna & Sollenberger,

2007). The current K-State Extension seeding rate recommendation for pearl millet grown in narrow rows under dryland conditions in western Kansas is 6-17 kg ha^{-1} and 11-22 kg ha^{-1} under irrigated conditions (Roozeboom et al., 2008). Using the seed weight of the pearl millet variety grown in our study, this converts to a recommended rate of between 0.75 and 2.126 M seeds ha^{-1} under dryland conditions and a recommended rate of between 1.376 and 2.752 M seeds ha^{-1} under irrigated conditions (Table 4.1).

Along with forage mass, forage nutritive value is important element of evaluating forages. Forage nutritive value has a significant influence on realized livestock gains for a given amount of forage (Newman et al., 2007). Forage yield and nutritive value are generally inversely related, so it is often important to find a balance between the two (Cusicanqui & Lauer, 1999; Huang et al., 2020; Liebert et al., 2023). Multiple measures are available to evaluate forage nutritive value, including concentrations of crude protein, fiber, and energy, as well as forage quality indices calculated using multiple individual measures.

Crude protein (CP) is measured by taking the total nitrogen content (as measured by the Kjeldahl digestion method) multiplied by 6.25 (Lee, 2018). Protein supplementation is the most expensive component in livestock feeding programs; therefore, forage crops with high crude protein content are highly desirable (Lemus, 2020). Crude protein can vary widely based on forage species, nitrogen fertility, and forage maturity. Generally, legumes are between 12%-25% CP, cool-season grasses are between 8%-23% CP, and warm-season grasses are between 5%-18% CP (Adesogan et al., 2017). As forages mature, crude protein content is diluted by increasing fiber, resulting in reduced nutritive value (Van Saun, 2023).

Fiber content is the best single predictor of feed intake and digestibility; therefore, fiber measures are also important for determining forage nutritive value (Lee, 2018). The two primary

fiber measures are acid detergent fiber (ADF) and neutral detergent fiber (NDF). Acid detergent fiber represents the plant's structural components (lignin, cellulose, silica, and insoluble nitrogenous compounds, but not hemicellulose). It is determined by weighing what remains after boiling in acid detergent. Neutral detergent fiber is what remains after boiling in neutral detergent and includes lignin, silica, cellulose, and hemicellulose. As ADF percentage increases, digestibility will generally decrease, and as NDF percentage increases, total dry matter intake will generally decrease (Benedict, 2012). Consequently, high-quality forages will have both lower ADF and NDF values. For grasses and legumes, ideal ADF fractions are less than 35% (Van Saun, 2023). Regarding NDF, for grasses, an NDF fraction below 50% is considered high-quality forage, and an NDF fraction above 60% is considered low-quality forage. For legumes, an NDF fraction below 40% is considered good, and above 50% is considered poor.

Occasionally, lignin content is measured independently because it can have a significant impact on forage quality. Sometimes referred to as the "woody part" of a plant, lignin is the primary factor influencing cell wall digestibility (Benedict, 2012). As lignin increases, digestibility, intake, and animal performance all decrease. Lignin content is primarily based on species and maturity (Kondo et al., 1987). As plants mature, their lignin content increases; in general, woody species, such as trees and shrubs, contain higher levels of lignin than grass species and legumes.

There are many different measures to quantify the total energy value of a forage. Total digestible nutrients (TDN) has been used for many years and is one of the most easily understood and widely recognized forage nutritive values (Adesogan et al., 2017). It is calculated as the sum of digestible protein, digestible crude fiber, digestible nitrogen-free extract, and 2.25 times the

digestible fat concentration. Higher TDN values indicate a higher quality forage, and TDN decreases as a plant matures.

Because there are many different measures of forage nutritive value, there have been a handful of efforts to index the various measures into a single value. The two most common indices are relative feed value (RFV) and relative forage quality (RFQ). RFV is the older of these two indices and uses NDF and ADF as predictors of forage quality (Adesogan et al., 2017). RFV ranks the quality of a cool-season forage relative to alfalfa at full bloom. The RFV of alfalfa at full bloom equals 100, so RFVs greater than 100 would be considered a higher quality forage than alfalfa at full bloom, and RFVs less than 100 would be a lower quality forage than alfalfa at full bloom. Because alfalfa is a temperate cool-season forage, RFV should be used only to evaluate other temperate cool-season forage species. RFQ is a newer index designed to apply to all forages (cool-season, warm-season, and tropical) except corn silage. It has the same mean and range as RFV, so it can be substituted for RFV when necessary. However, RFQ is based on CP, NDF, ADF, fat, ash, and NDFd, so comparing RFQ scores with RFV scores should be avoided whenever possible.

This study aims to determine how changing seeding rates impact forage mass, biophysical traits, forage nutritive value, and profitability of the four aforementioned species. Existing research on the impact of seeding rate on forage mass varies greatly. Mekasha et al. (2022) found that the seeding rate significantly impacted dry matter accumulation in dual-purpose sorghum in a study that included seeding rates of 12.5, 25, 50, 75, and 100 kg of seed ha^{-1} (between 0.394 M and 4.15 M seeds ha^{-1}) for a study that was conducted across three sites in the Central Rift Valley region of Ethiopia. In a study examining biomass sorghum for energy production, Snider et al. (2012) found that sorghum biomass yield was not significantly affected by increasing the seeding

rate from 116,000 to 291,000 seeds ha^{-1}. However, yield decreased when the seeding rate was increased from 218,000 to 393,000 seeds ha^{-1} for a study conducted in the Southeastern United States. In a Brazilian study on biomass sorghum, which included plant populations of 80,000, 100,000, 120,000, and 140,000 plants ha^{-1} and row spacings of 0.5, 0.7, 0.9, and 1.1 m, May et al. (2016) found that row spacing influenced the fresh biomass yield of sorghum significantly more than the plant population. This was because losses in plant population were compensated by tillering, and tillering was greatest in the narrowest row spacing within a given population (May et al., 2016). In a study from Pennsylvania that compared seeding rates of 200,000 seeds ha^{-1} and 300,000 seeds ha^{-1} for forage sorghum silage, Elango et al. (2020) found no significant difference between seeding rates in terms of dry matter yield.

Results vary for how morphological traits, such as plant height, tillers, and stalk diameter, respond to seeding rate. Mekasha et al. (2022) and Snider et al. (2012) found that seeding rate had different impacts on plant height at various locations. Most studies showed that the seeding rate and plant height either exhibited a statistically significant inverse relationship or no statistically significant relationship. In a study on the impacts of seeding rate in pearl millet, Bouchard et al. (2011) found a significant inverse relationship between seeding rate and number of tillers. Mekasha et al. (2022) found a significant inverse relationship between stalk diameter and seeding rate at all three locations of their study.

Finally, regarding forage nutritive value, Mekasha et al. (2022) found that increasing the seeding rate significantly decreased NDF, ADF, and acid detergent lignin, while leading to an increase in in vitro organic matter digestibility, resulting in an overall improvement in forage nutritive value. However, the seeding rate did not significantly affect CP (Mekasha et al., 2022).

Elango et al. (2020) found no significant difference in CP fraction, starch content, NDFD, or net energy lactation between forage sorghum seeded at 200,000 seeds ha^{-1} and 300,000 seeds ha^{-1}.

Based on these results, we hypothesized that forage yields would be maximized at different seeding rates for different species depending on the environment. Regarding biophysical traits and forage nutritive value, we hypothesized that increasing the seeding rate would result in smaller stalk diameters, a greater leaf-to-stem ratio, and forage with lower fiber concentrations and higher crude protein concentrations.

Materials and methods

Treatments

This study was conducted from 2022 to 2024. In 2022 and 2023, we planted four species (forage sorghum, sorghum-sudan, sudangrass, and pearl millet) at six different seeding rates (0.37 M, 0.74 M, 1.11 M, 1.48 M, 1.85 M, and 2.22 M seeds ha^{-1}). In 2024, we planted only forage sorghum but at seven different seeding rates (0.37 M, 0.74 M, 1.48 M, 2.22 M, 2.96 M, 3.7 M, and 4.44 M seeds ha^{-1}). The variety name, seed weight, and pure live seed percentage of the species studied are listed in Table 4.1.

Experimental layout

This study was conducted at the K-State Southwest Research-Extension Center near Garden City, KS, and the K-State Agricultural Research Station near Hays, KS. In Garden City, we conducted irrigated trials at coordinates 37.9856018, -100.8140431, with a Ulysses silt loam soil series and slopes ranging from 0 to 1 percent. We conducted dryland trials at coordinates 37.990274, -100.827261, with a Beeler silt loam soil series and slopes ranging from 0 to 1 percent. In Hays, we only conducted dryland trials. These trials were conducted at coordinates 38.858238, -99.322694, which had a Roxbury silt loam, rarely flooded soil series with slopes

ranging from 0 to 2 percent. Initially, we planned a dryland and irrigated trial for Garden City in 2022; however, the dryland trial failed to establish, so only an irrigated trial was conducted at Garden City in 2022. To compensate for the lost dryland trial in 2022 at Garden City, a dryland trial was added in 2023 at Hays, along with dryland and irrigated trials at Garden City. In 2024, we conducted dryland trials at Hays and Garden City, as well as an irrigated trial in Garden City. In Garden City, plots were 9.1 m × 4.6 m, and in Hays, plots were 9.1 m × 3m. The study employed a randomized complete block design with four replications of each species-seeding rate combination in a factorial treatment structure.

Crop management and harvest procedure

The crops were managed as follows. We planted to a depth of 25 mm and in rows spaced at 203 mm at both locations. Planting occurred between June 1st and July 1st for each trial. In Garden City, we planted with a Fabro no-till plot drill (Fabro, Swift Current, Canada). In Hays, we planted with a Great Plains 3P1006NT no-till drill (Great Plains, Salina, KS). Prior to planting, 1,000 seeds of each species were counted and weighed to determine the seed weight. This seed weight per 1,000 seeds was then used to properly determine the amount of seed needed for each plot dependent on seeding rate and species. At planting, the seeds were metered through a calibrated zero-max distribution cone mounted on the drill.

Approximately a month before planting, all plots received a burndown treatment of 0.15 L ha^{-1} of saflufenacil, 2.4 L ha^{-1} of glyphosate [N-(phosphonomethyl) glycine], and 2.4 L ha^{-1} of methylated seed oil (MSO). We applied a separate application of atrazine at a rate of 2.4 L ha^{-1} applied closer to, but still before planting, for residual weed control. All plots received 56.1 kg ha^{-1} application of mono-ammonium phosphate (MAP, 11-52-0) at planting as well as an additional

application of urea fertilizer (46-0-0) at a rate of 50.5 kg ha^{-1}. In total, plots received 29.4 kg ha^{-1} of nitrogen and 29.2 kg ha^{-1} of phosphorus.

Crops in the irrigated trials did not receive a set irrigation regimen but instead were irrigated as needed. Thus, the amount of irrigation applied varied from year to year based on precipitation during the growing season. In 2022, the driest year, 318 mm of irrigation were applied over the course of the growing season. However, in 2023 and 2024, which were much wetter years (Table 4.2), only 102 mm of irrigation were applied each growing season.

We harvested when 50% of the plants in a plot had headed. In Garden City, we harvested with an RTech Forage Harvester (RTech, MB, Canada) with a 1.5 m-wide cutting head. In Hays, we harvested with a Carter flail forage harvester (Carter Manufacturing Company, Inc., Brookston, IN) with a one m-wide cutting head. Plants were harvested at a height of 8 cm. A 0.7 kg sub-sample of the freshly harvested material was collected and dried at 40 °C until the weight was constant. Once dried, we weighed the sample, and we divided the weight by the wet weight to determine the percentage of dry matter for each plot. We multiplied the percentage of dry matter by the initial fresh forage weight to calculate the forage biomass yield for each plot.

Biophysical measurements

We took the following biophysical measurements for each treatment: establishment rate, tillers per plant, plant height, leaf-to-stem ratio, and stalk diameter. To calculate the establishment rate, a stand count was taken two weeks after planting, but before tillering, by counting the number of plants in two randomly selected one-meter rows per plot. Those values were scaled up to provide a plant population in terms of plants ha^{-1}. We divided that value by the initial seeding rate of the plot to calculate an establishment rate for each plot. At the end of the growing season, we repeated this process, but this time we counted every stem in the one-meter row. This process

provided an estimate of the total number of stems ha^{-1}. We divided that value by the plant population that we determined at the beginning of the growing season to calculate stems per plant. The stems per plant value was subtracted by one to account for the main stalk to calculate tillers per plant.

A few days before harvest we measured plant height in meters by holding a measuring stick up to each plot and determining the approximate height at eye level of the top of the plot. To calculate stalk diameter, after harvest, we cut five randomly selected plants from the remaining sections of the plot at a height of 7 cm. Then we cut again at 38 cm, measuring from the ground level, creating a 31 cm long stalk segment. We dried the stalk segments at 40 °C until the weight was constant. Once dried, the diameter of the stalk was measured with a caliper at both the top and bottom of the cut stalk, resulting in ten total measurements. The average of these ten measurements was taken to give an estimate of the stalk diameter for each plot.

To calculate the leaf-to-stem ratio, after harvest, we randomly selected five plants from the unharvested sections of each plot. We separated leaves and stems and dried both at a temperature of 40ºC until the weight was constant. Once dried, we measured the weight of the stems and leaves separately and calculated the leaf-to-stem ratio by dividing the weight of the leaves by the weight of the stems.

Forage nutritive analysis

After being dried and weighed, samples used for determining forage dry matter concentration were ground using a 4 Bench Wiley Mill fitted with a 2-mm screen (model number T4724E25, Thomas Scientific, Chadds Ford Township, PA), then with a UDY Cyclone Sample Mill fitted with a 1-mm screen (model number 3010-014, UDY, Fort Collins, CO). The ground samples were analyzed for crude protein (CP), acid-detergent fiber (ADF), neutral detergent fiber

(NDF), lignin, and starch using NIR (near infrared) spectroscopy, calibrated to NIRS Consortium standards for warm-season annual grasses. Total digestible nutrients (TDN) and relative forage quality (RFQ) were calculated using the other measured forage nutritive values (Weiss, 1998; Moore & Undersander, 2002). Forage nutritive analysis was conducted only for the 2022-23 trials. We calculated the forage nutritive value per area by multiplying the CP concentration and TDN concentration by the forage mass to produce CP and TDN yields in kg ha^{-1}.

Economic analysis

The economic analysis considered only expenses and revenues that were variable among treatments and trials. Thus, we only factored seed cost, crop value, and irrigation cost into the economic analysis conducted in this study. All other economic factors that may affect total profitability, such as drilling, herbicide, and fertilizer costs, were excluded from our analysis because they remained constant across treatments and trials. Due to their genetic similarity and consistency in results across other variables, data from sorghum-sudan and sudangrass were combined in the economic analysis. We analyzed forage sorghum and pearl millet independently.

Seed costs for all species were estimated at \$3.30 kg^{-1} because that value represented an approximate average seed costs across multiple sources, including Kansas State University Agricultural Economics department crop budgets and online advertised seed costs from seed dealers (Ibendahl et al., 2023; Green Cover, 2024; Albert Lea Seed, 2024). We estimated hay prices at \$0.12 kg^{-1} based on an average of a sample of USDA Southwest Kansas Direct Hay Reports published between 2022 and 2024 (USDA Agricultural Marketing Service, 2022-2024). Irrigation energy and labor cost rates were taken as an average from the 2022-24 Kansas AgManager Southwest Kansas Irrigated Grain Sorghum Cost-Return Budgets because an irrigated forage sorghum budget was not available (Ibendahl et al., 2022-24). We calculated

partial economic returns for each plot by subtracting variable expenses (seed and irrigation costs) from the crop value.

After calculating the partial economic returns for each species in each trial, we conducted a sensitivity analysis adapted from Bourgalt et al. (2024) and Cox and Cherney (2014) for each species under both irrigated and dryland conditions to see how changing the seeding rate affected profitability across varied seed costs and hay prices. The hypothetical seed costs analyzed were \$1.10, \$3.30, and \$5.50 ha^{-1}, and the hypothetical hay prices were \$0.06, \$0.09, \$0.12, \$0.15, and \$0.18 kg^{-1}. For irrigated forage sorghum, this sensitivity analysis considered the effect of increasing seeding rates from 2.22 M seeds ha^{-1} to 4.44 M seeds ha^{-1}. For dryland forage sorghum, a change in seeding rate from 1.48 M seeds ha^{-1} to 2.22 M ha^{-1} was analyzed. For irrigated sorghum-sudan, sudangrass, and pearl millet, we analyzed an increase in seeding rate from 1.11 M seeds ha^{-1} to 2.22 M seeds ha^{-1}, and for these same crops in dryland conditions, we considered an increase in seeding rate from 0.74 M seeds ha^{-1} to 1.85 M seeds ha^{-1}.

Statistical analysis

All non-economic data analyses were performed using PROC GLIMMIX in SAS Studio ver. 3.82 (SAS Institute, 2023, Cary, NC). For the 2022 and 2023 data, we analyzed the Garden City and Hays data independently of each other because the data from the two sites did not pass Bartlett's test for homogeneity of variance. For the Garden City analysis, species, seeding rate, and environment (a variable created to capture the three separate trials at Garden City: 2022 irrigated, 2023 irrigated, and 2023 dryland), and their interactions were treated as fixed effects, while replication was considered a random effect. For the data analysis from Hays, species, seeding rate, and their interaction were considered fixed effects, while we treated replication as a random effect.

In 2024, there was no analysis of forage nutritive values. The variables forage yield, establishment, plant height, tillers per plant, and leaf-to-stem ratio were analyzed separately for irrigated and dryland trials. For the dryland trials, we considered seeding rate, location, and their interaction as fixed effects, while we treated rep as a random effect. For the irrigated trial analysis, seeding rate was the only fixed effect, and replication was a random effect. In 2024, we collected stalk diameter data only in Garden City; therefore, we analyzed the Garden City irrigated and dryland trials together for stalk diameter, with seeding rate, irrigation, and their interaction treated as fixed effects and replication treated as a random effect. For all analyses, we considered treatment effects significant at $P \leq 0.05$. Means were separated using pairwise comparisons with no adjustment. Pearson correlation coefficients among response variables were generated using PROC CORR. Treatment means for partial economic returns were separated using the least significant difference (LSD) generated from the PROC GLM analysis of variance.

Results

Weather

The most likely reason the 2022-23 Garden City and Hays trials failed Bartlett's homogeneity of variance test is that the three Garden City trials ended up being vastly different environments from the Hays trial due to significant differences in water availability. Two of the three Garden City trials were irrigated, and the 2023 dryland trial took place in an exceptionally wet year (Table 4.2). In 2023, Garden City received 21.2% more precipitation than the 60-year annual average. Notably, the total rainfall from May to August was 35.6% greater than the typical amount of precipitation for that period. This means the crops in the 2023 dryland trial at Garden City experienced little to no water stress. This possibly explains the lack of an environment or an environment by seeding rate interaction effect on forage yield for the 2022-23

Garden City trials (Table 4.3). This suggests that, due to the high precipitation in 2023 at Garden City, irrigation had no significant effect on forage yield when comparing the 2023 Garden City dryland trial to the 2022 and 2023 irrigated trials.

On the other hand, in 2023, Hays received below-average precipitation (80 mm less precipitation between May and August than Garden City in 2023) (Table 4.2). Thus, the 2023 dryland trial in Garden City had conditions similar to the two irrigated trials than to the 2023 dryland Hays trial. Consequently, dryland Hays trial was the only trial in 2023 that was somewhat representative of a typical dryland growing environment for the region. In 2024, the weather conditions were comparable at both sites, with Garden City receiving slightly above-average rainfall and Hays receiving slightly below-average rainfall. Hays received 339 mm of precipitation between May and August, and Garden City received 317 mm of precipitation between May and August, resulting in a very similar growing environment in terms of precipitation for the two dryland trials in 2024 (Table 4.2).

Seeding rate, establishment rate, and plant population

To begin, the relationship between seeding rate, establishment rate, and plant population warrants a brief discussion. These three variables were highly interrelated and exhibited significant correlational relationships with nearly every other variable in this study; therefore, they serve as a logical starting point for our analysis (Table 4.4). Plant population is simply the seeding rate multiplied by the establishment rate. While plant population had a slightly stronger correlative relationship than seeding rate with many of the other variables in the study, including forage yield, tillers per plant, crude protein, NDF, ADF, TDN, and RFQ, we decided to focus our analysis primarily on the effects of seeding rate instead of plant population. This was because one of the objectives of this study was to provide seeding rate recommendations to farmers, helping

them understand how seeding rate specifically affects the forage yield, quality, and profitability of the species in this study. It could be argued that because plant population had a stronger correlative relationship with some of the response variables in our study, the best way to develop a recommended seeding rate would be to analyze the effect of plant population on forage yield, forage quality, and profitability, and then convert the ideal plant population back into a recommended seeding rate. That approach presupposes a constant establishment rate that exists to make a conversion between plant population and seeding rate. However, in all tested environments, our results showed that the seeding rate itself had a significant effect on establishment rate, meaning that when the seeding rate was manipulated, there was not a single establishment rate that could be used to convert plant population back into a specific seeding rate (Table 4.3; Table 4.5; Table 4.6).

The establishment rate tended to fall as the seeding rate increased, and the correlation coefficient between the two variables was –0.25 across trials conducted in 2022 and 2023, a statistically significant value. This trend was particularly evident in the 2023 Hays dryland trial, where establishment rate fell from 92.9% at a seeding rate of 0.37 M seeds ha^{-1} to 54.6% at a seeding rate of 2.22 M seeds ha^{-1}, with the lowest two seeding rates having statistically significant greater establishment rates than the four highest seeding rates (Table 4.7). The same trend was evident in the 2024 forage sorghum seeding rate trials, where, under dryland conditions, the establishment rate decreased as the seeding rate increased (Table 4.8). The trend was similar in the 2024 irrigated forage sorghum trial, where the establishment rate at a seeding rate of 0.37 M seeds ha^{-1} was significantly greater than the establishment rate of all other seeding rates except a seeding rate of 0.74 M seeds ha^{-1} (Table 4.9). This reduction in establishment rate as seeding rate increases could be due to increased competition stress between individual plants.

Seeding rate was not the only thing that affected establishment rate. In the 2022-23 trials at Garden City, we observed a significant species-by-environment interaction effect on establishment rate (Table 4.3). Similarly, in the 2023 trial at Hays, species had a significant effect on establishment (Table 4.5). At all four trials in 2022 and 2023, pearl millet had the lowest establishment rate of the four grasses tested and had a significantly lower establishment rate than all three other species in both the 2022 irrigated trial and the 2023 Hays trial (Table 4.10; Table 4.11). This could be because pearl millet has slower early growth than sorghums making it more susceptible to weed competition (Kumar et al., 2024). We also found varying establishment rates between environments. We expected this variation because establishment rate can be affected by seedbed physical, chemical, and biological components as well as management practices such as tillage, herbicide use, and previous crop choice (Lamichhane et al., 2018).

Forage mass

The relationship between seeding rate and forage mass was complicated and varied depending on the growing environment and species. In the 2022 and 2023 Garden City trials, our initial model did not find a significant interaction between seeding rate and species at a significance level of $P \leq 0.05$ (Table 4.3). However, with a P-value for the species × seeding rate interaction that was still relatively low ($P = 0.089$) and the fact that we were interested in identifying an ideal seeding rate for each individual species in the study, we decided to split up our analysis of the impact of seeding rate on forage mass by species. When we conducted this analysis, we found some significant differences in how seeding rate affected forage yield within each of the four species in the study (Table 4.12).

For the 2022 and 2023 trials at Garden City, which included two irrigated environments and one abnormally wet non-irrigated environment, the general relationship between seeding rate and forage yield for sorghum-sudan, sudangrass, and pearl millet was one in which forage yield would initially significantly increase with an increase in seeding rate. However, it would hit a plateau point where significant yield increases no longer occurred as the seeding rate continued to increase (Table 4.12). Yields did not increase significantly beyond 1.48 M seeds ha^{-1} for sorghum-sudan and sudangrass and beyond 1.1 M seeds ha^{-1} for pearl millet. On the other hand, in the 2022-23 Garden City trials, forage sorghum did not show the same plateauing yield behavior as the other species. The highest seeding rate, 2.22. m seeds ha^{-1}, had a significantly greater forage yield than all other seeding rates tested.

Because forage sorghum forage yields did not appear to plateau based on the data of the 2022-23 Garden City trials, in 2024, we decided to conduct additional research on forage sorghum that included higher seeding rates. Under dryland conditions in 2024, forage sorghum forage yields displayed a plateau response to seeding rate increases as the other species in the 2022-23 Garden City trials. For the dryland trials in 2024, forage mass did not increase significantly beyond 1.48 m seeds ha^{-1} (Table 4.8). The 2024 dryland trials had precipitation amounts typical of semi-arid Great Plains growing environment than the 2023 dryland trial in Garden City (Table 4.2). This suggests that under typical climatic conditions for the region, without irrigation, forage sorghum forage yields have a plateau relationship with seeding rate.

The 2024 irrigated forage sorghum seeding rate trial provided less conclusive results. Our model showed no significant effect of seeding rate on forage yield (Table 4.6). However, the highest seeding rate tested, 4.44 m seeds ha^{-1}, had an 11% greater forage yield than any other seeding rate tested and a 90% greater forage yield than the lowest yielding seeding rate tested,

0.74 m seeds ha^{-1} (Table 4.9). The reason this large jump in forage mass between the lowest yielding seeding rate and the highest yielding seeding rate was not statistically significant was because of the high level of variance that occurred in this trial. The coefficient of variance for the 2024 Garden City irrigated trial was 34.8, while the coefficient of variance for the 2024 Garden City dryland trial and 2024 Hays dryland trial were 27.9 and 23.9, respectively.

The 2023 Hays dryland trial did not have a significant interaction effect between seeding rate and species for forage mass (Table 4.5). However, seeding rate did have a significant effect on forage mass. The greatest forage mass occurred at the highest seeding rate, and the 2.22 M seeds ha^{-1} rate had a significantly greater forage mass than the 0.37 M seeds ha^{-1} or the 1.11 M seeds ha^{-1} rates (Table 4.7). However, the relationship between forage mass and seeding rate was not strictly linear at the 2023 Hays dryland trial. The 0.74 M seeds ha^{-1} rate, the second-lowest seeding rate, was not statistically significantly different from the highest seeding rate in terms of forage mass. This spike in forage mass at the second-lowest seeding rate, followed by a subsequent drop in forage mass at the third-lowest seeding rate, makes it hard to determine a definitive agronomic optimum seeding rate for the 2023 Hays dryland trial. The 2023 Hays dryland trial was the most water-limited trial in the study (Table 4.2). The complicated relationship between seeding rate and forage mass at the 2023 Hays dryland trial may suggest that forage mass gains due to seeding rate increases are less reliable in low-moisture environments.

Species also had a significant effect on forage yield at all sites of the 2022-23 trials (Table 4.10; Table 4.11). Averaged across all seeding rates, pearl millet had significantly lower yields than the three other species in the study during the 2022 irrigated trial and the 2023 Hays dryland trial, with the other three species having statistically equivalent forage yields during

those site-years. At the 2023 Garden City dryland trial, the following relationship for forage yield occurred among the species: sorghum-sudan = sudangrass > pearl millet = forage sorghum (Table 4.10). At the 2023 irrigated trial, the following relationship occurred: sorghum-sudan = forage sorghum > sudangrass = pearl millet. Sorghum-sudan was the highest-yielding species in three of the four 2022-23 environments and was the only species that never yielded significantly less than any other species, regardless of environment (Table 4.10; Table 4.11).

Biophysical traits

The first biophysical trait considered was plant height. At the 2022-23 Garden City trials, we observed a significant main effect of seeding rate and a significant interaction effect between species and environment on plant height (Table 4.3). Seeding rate and plant height had a statistically significant inverse relationship, with plant height decreasing as seeding rate increased (Table 4.4; Table 4.12). The 2024 forage sorghum trials also demonstrated this relationship (Table 4.6; Table 4.7; Table 4.8).

In the 2022-23 trials at both Hays and Garden City, sorghum-sudan had the tallest plants and was significantly taller than all other species in the study. This trend continued in the 2023 trials at Garden City, under both dryland and irrigated conditions (Table 4.10; Table 4.11). Pearl millet was significantly shorter than all other species in the 2023 irrigated trial. However, forage sorghum was significantly shorter than all other species in the 2023 dryland trials at both Hays and Garden City. In the 2022 irrigated trial, pearl millet and forage sorghum were essentially equivalent in height, but both were significantly shorter than sudangrass or sorghum-sudan.

The plants in the 2023 Garden City dryland trial, averaged across all species and seeding rates, were significantly shorter than the plants in either of the Garden City irrigated trials (Table 4.10). This result suggests that the availability of water is directly related to plant height. The

results from the 2023 Hays dryland trial, the trial with the lowest rainfall, further support this hypothesis because the plants in this trial were, on average, shorter than those in any of the Garden City trials (Table 4.11). Interestingly, the 2023 Hays trial was also the only trial where no significant relationship was found between plant height and seeding rate. This result suggests that in extremely water-limited environments, the effect of seeding rate on plant height is diminished, if not eliminated (Table 4.7).

Moving on to our analysis of tillering, three factors influenced the number of tillers per plant: seeding rate, species, and environment. Seeding rate and tillers per plant had a significant inverse relationship (Table 4.4). In every environment of the 2022-23 trials, the lowest seeding rate, across all species, produced significantly more tillers than any of the other seeding rates (Table 4.7; Table 4.13). This relationship also occurred within every species for the 2022-23 Garden City trials (Table 4.12). Species also had a significant effect on the amount of tillering. In the 2023 Hays trial, pearl millet tillered significantly more than any of the other species. In the 2022-23 Garden City trials, the relationship between species and tillers per plant was as follows: pearl millet > sudangrass > sorghum-sudan = forage sorghum (Table 4.11; Table 4.12).

The environment also had a significant effect on tillering. In the 2022-23 Garden City trials, across all species and seeding rates, the two irrigated environments had significantly more tillers per plant than the dryland environment (Table 4.10). The 2023 Hays trial averaged 0.96 tillers per plant across seeding rate and species, a similar number to the 2023 Garden City dryland trial (Table 4.7; Table 4.10). At the 2022-23 Garden City trials, we observed a significant interaction between seeding rate and environment, as well as between species and environment, for tillers per plant (Table 4.3). The crux of this interaction was that in dryland environments, the differences in tillers per plant among the various seeding rates and species

were compressed as compared to the irrigated environments. For example, the average difference in tillers per plant between the lowest and highest seeding rates, across all species, in the 2022-23 irrigated trials, was 2.28 tillers. However, in the 2023 Garden City dryland trial, this difference was only 1.22 tillers (Table 4.13). This relationship also occurred in the differences in tillers per plant among species. In the 2022-23 irrigated trials, the average difference in tillers per plant, across all seeding rates, between pearl millet, the species with the greatest tillering, and forage sorghum, the species with the least tillering, was 1.15 tillers. However, in the 2023 Garden City dryland trial, this difference was only 0.32 tillers (Table 4.10). These results suggest that, while differences in tillering among seeding rates and species occurred in every trial of this study, these differences were generally more pronounced in irrigated environments than in dryland environments (Table 4.7; Table 4.8; Table 4.9; Table 4.10; Table 4.13).

Leaf-to-stem ratio had a complex relationship with seeding rate. When analyzed across all trials and species for the 2022-23 data, there was no statistically significant linear relationship with seeding rate (Table 4.4). However, when broken out by species at both Garden City and Hays in 2022-23, seeding rate had a significant effect on leaf-to-stem ratio in sorghum-sudan at Garden City and in every species except Sudangrass at Hays (Table 4.12; Table 4.14). However, in none of the species that exhibited a significant effect of seeding rate on leaf-to-stem ratio was the relationship between the two clearly linear. Beyond that, the different species displayed somewhat contradictory relationships. At Garden City for sorghum-sudan, the highest leaf-to-stem ratio occurred at a seeding rate of 1.85 M seeds ha^{-1}, but at Hays, this seeding rate produced the lowest leaf-to-stem ratio in sorghum-sudan (Table 4.12; Table 4.14). In pearl millet at Hays, the lowest seeding rate had the greatest leaf-to-stem ratio, but in forage sorghum at Hays, the highest seeding rate had the greatest leaf-to-stem ratio. The 2024 forage sorghum trials further

complicated these results. However, in the 2024 forage sorghum trials, it had a significant effect in all environments (Table 4.9; Table 4.15). There was no clear linear relationship between seeding rate and leaf-to-stem ratio in the 2024 trials. However, generally, the lowest leaf-to-stem ratios occurred at the lowest seeding rates, with the notable exception that the highest seeding rate at Hays had a leaf-to-stem ratio as low as the lowest two seeding rates (Table 4.9; Table 4.15). Given all of this, our results do not suggest a clear pattern in the relationship between seeding rate and leaf-to-stem ratio.

Species significantly affected the leaf-to-stem ratio in all environments of the 2022-23 trials; however, this effect was not consistent across the trials (Table 4.10; Table 4.14). Averaged across seeding rate, sorghum-sudan had either the greatest leaf-to-stem ratio or a statistically equivalent leaf-to-stem ratio to the species with the greatest leaf-to-stem ratio at all three trials in Garden City, but in Hays, the relationship between species and leaf-to-stem ratio was as follows: forage sorghum > sudangrass = sorghum-sudan > pearl millet (Table 4.10; Table 4.14). The 2023 Hays trial had significantly higher leaf-to-stem ratios across all seeding rates and species than any of the 2022-23 Garden City trials. However, in the 2024 forage sorghum trials, this trend did not continue. In 2024, the average leaf-to-stem ratio of the dryland Hays and dryland Garden City trials was about the same, but both were much greater than the average leaf-to-stem ratio of the irrigated trial (Table 4.9; Table 4.15).

The final biophysical trait considered was stalk diameter. The magnitude of the correlation between seeding rate and stalk diameter was greater than that of seeding rate with any other biophysical trait or forage nutritive value (Table 4.4). As the seeding rate increased, stalk diameter decreased. (Table 4.7; Table 4.12; Table 4.13; Table 4.16). This was true for all species and environments.

Species also had a significant effect on stalk diameter in every environment of the 2022-23 trials (Table 4.10; Table 4.11). In Garden City, across seeding rate and environment, species had the following relationship with stalk diameter: forage sorghum > pearl millet = sorghum-sudan > sudangrass (Table 4.12). In Hays, the relationship was as follows: forage sorghum ≥ pearl millet = sorghum-sudan ≥ sudangrass (Table 4.11).

Forage nutritive values

We measured six different forage nutritive values: CP, NDF, ADF, lignin, TDN, and RFQ. When analyzed across all species and seeding rates for the 2022-23 trials, seeding rate had a significant negative correlation with CP, but it was not a particularly strong correlation (Table 4.4). In the 2022-23 Garden City trials, neither seeding rate nor any of its interactions had a significant effect on CP (Table 4.3). In the 2023 Hays trial, seeding rate had a significant effect on CP, with the two highest seeding rates having the lowest CP concentrations (Table 4.5; Table 4.7). This is likely related to the increase in yield seen with an increase in seeding rate, resulting in a dilution of CP concentration (Table 4.7).

Species, environment, and their interaction all had a significant effect on CP concentration in the 2022-23 Garden City trials (Table 4.3). There were no significant differences between species for CP concentration in the two irrigated environments, but in the 2023 Garden City dryland trial, the following relationship occurred: pearl millet ≥ forage sorghum ≥ sudangrass ≥ sorghum-sudan (Table 4.17; Table 4.18; Table 4.19). In the 2023 Hays trial, pearl millet had a significantly greater CP concentration than all the other species (Table 4.11). The fact that pearl millet had the greatest CP concentration in both dryland trials was potentially caused by the inverse relationship between CP concentration and yield (Table 4.4). In the 2023 Hays trial, pearl millet significantly lagged the other three species in terms of forage

mass (Table 4.11). In the 2023 Garden City dryland trial, the order of species from least to greatest in terms of forage mass was the exact opposite of the order of species from least to greatest in terms of CP concentration giving further credence to the possibility that differences in forage mass was the primary driver of differences in CP concentration between species (Table 4.10; Table 4.19).

We analyzed three different measures that examined various types of fiber in the crop: NDF, ADF, and lignin concentration. There was no significant correlation between seeding rate and NDF or ADF; however, a weak yet significant negative correlation was observed between seeding rate and lignin concentration (Table 4.4). In the 2022-23 Garden City trials, all three of these measures were significantly affected by the three-way interaction between seeding rate, species, and environment (Table 4.3). In each environment of the Garden City trials, within sorghum-sudan, only seeding rate had a significant effect on NDF concentration (Table 4.17; Table 4.18; Table 4.19). In the 2022 irrigated trial, the relationship between seeding rate for sorghum-sudan was 1.11 M seeds ha^{-1} = 1.48 M seeds ha^{-1} ≥ 0.74 M seeds ha^{-1} = 0.37 M seeds ha^{-1} ≥ 1.85 M seeds ha^{-1} = 2.22 M seeds ha^{-1} (Table 4.17). In the 2023 irrigated trial, sudangrass was the species where seeding rate had a significant effect on NDF concentration. The only seeding rates that had significant differences were 1.48 M seeds ha^{-1} (the highest NDF concentration) and 1.11 M seeds ha^{-1} (the lowest NDF concentration) (Table 4.18). In the 2023 Garden City dryland trial, seeding rate had a significant effect on NDF concentration for pearl millet. In this environment within pearl millet, NDF concentration appeared to increase as seeding rate increased, with the lowest seeding rate having a significantly lower NDF concentration than the two highest seeding rates (Table 4.19). In the 2023 Hays trial, seeding rate had a significant effect on NDF concentration, but the relationship was not linear, with the

second-lowest and the second-highest seeding rates having the highest NDF concentrations (Table 4.5; Table 4.7). In conclusion, while seeding rate had a significant effect on NDF concentration in some cases, there was no consistent pattern for the effect of seeding rate on NDF concentration.

There were significant differences in NDF concentration among species only at the 2023 Hays trial and the 2023 Garden City dryland trial (Table 4.11; Table 4.19). At the 2023 Hays trial, pearl millet had a significantly lower NDF concentration than the other species, while there were no significant differences among the other three species (Table 4.11). The relationship between species and NDF concentration at the 2023 Garden City trial was as follows: sorghum-sudan ≥ sudangrass ≥ pearl millet = forage sorghum (Table 4.19). These results suggest that in dryland environments, pearl millet may have lower NDF concentrations than the other species in the study.

Turning to ADF concentration, in the 2022 irrigated trial, there was a significant effect of seeding rate within sorghum-sudan and pearl millet (Table 4.17). In sorghum-sudan, the relationship was as follows: 1.11 M seeds ha^{-1} ≥ 1.48 M seeds ha^{-1} ≥ 0.74 M seeds ha^{-1} = 0.37 M seeds ha^{-1} ≥ 1.85 M seeds ha^{-1} ≥ 2.22 M seeds ha^{-1}. In pearl millet, the only two seeding rates with significant differences were the highest seeding rate, resulting in the highest ADF concentration, and the lowest seeding rate, resulting in the lowest ADF concentration. In the 2023 irrigated trial, sudangrass was the only species in which seeding rate had a significant effect on ADF concentration (Table 4.18). The relationship was as follows: 1.48 M seeds ha^{-1} ≥ 1.85 M seeds ha^{-1} ≥ 2.22 M seeds ha^{-1} = 0.37 M seeds ha^{-1} ≥ 0.74 M seeds ha^{-1} ≥ 1.11 M seeds ha^{-1}. Seeding rate did not have a significant effect on ADF concentration in any species in the 2023 Garden City dryland trial (Table 4.19). In the 2023 Hays trial, seeding rate had a significant

effect on ADF concentration, but the relationship was not linear, with the second-lowest and the second-highest seeding rates having the highest NDF concentrations (Table 4.5; Table 4.7). Similarly to NDF concentration, even though seeding rate had a significant effect on ADF concentration in some instances, there was no overarching trend in the relationship between ADF concentration and seeding rate. There were no significant differences in ADF concentration by species in any environment of the 2022-23 Garden City trials (Table 4.17; Table 4.18; Table 4.19). Species had a significant effect on ADF concentration in the 2023 Hays trial. However, the only two species that differed significantly were sorghum-sudan, with the highest ADF concentration, and pearl millet, with the lowest ADF concentration (Table 4.11).

The final fiber measure evaluated was lignin concentration. In the 2022 irrigated trial, there were no significant differences in lignin concentration among species; however, within sorghum-sudan, seeding rate had a significant effect on lignin concentration (Table 4.17). The significant differences were between the 2.22 M seeds ha^{-1} seeding rate, which had the lowest lignin concentration, and the 1.11 M and 1.48 M seeds ha^{-1} seeding rates, which had the highest lignin concentration. In the 2023 irrigated trial, neither seeding rate nor species had a significant effect on lignin concentration (Table 4.18). In the 2023 dryland Garden City trial, three species saw significant differences in lignin concentration between seeding rates: forage sorghum, sudangrass, and pearl millet (Table 4.19). Sudangrass and pearl millet exhibited a general trend where, as the seeding rate increased, lignin concentration decreased. On the other hand, forage sorghum did not exhibit this clear relationship. Instead, 1.85 M seeds ha^{-1} was the only seeding rate to have less lignin compared to the other seeding rates. There was also a significant species main effect, across seeding rates, on lignin concentration in the 2023 Garden City dryland trial. The relationship was as follows: pearl millet ≥ forage sorghum = sudangrass ≥ sorghum-sudan.

In the 2023 Hays trial, the interaction between seeding rate and species had a significant effect on lignin concentration (Table 4.14). Within two species, the seeding rate had a significant effect on lignin concentration: sorghum-sudan and sudangrass. In sorghum-sudan, the only difference among seeding rates was that the 2.22 M seeds ha^{-1} seeding rate had a significantly lower lignin concentration than the 1.48 M and 1.85 M seeds ha^{-1} seeding rates. In sudangrass, the only difference among seeding rates was that the 0.74 M seeds ha^{-1} seeding rate had a significantly greater lignin concentration than the 0.37 M and 1.11 M seeds ha^{-1} seeding rates. There was a significant main effect of species across seeding rates on lignin concentration in the 2023 Hays trial. However, the only difference among species was that forage sorghum had a significantly lower lignin concentration than all other species in the trial. Given all the results of the 2022-23 trials, there were no clear trends in how either seeding rate or species affected lignin concentration. However, one thing to note is that there were more significant differences between seeding rates within species and between species across seeding rates in the two dryland trials than in the two irrigated trials (Table 4.14, Table 4.17, Table 4.18, Table 4.19). This result suggests that differences in lignin concentration due to seeding rate or species may be exaggerated in drier environments and minimized in wetter environments.

The next forage nutritive value we analyzed was TDN concentration. There was no significant correlation between seeding rate and TDN concentration (Table 4.4). However, the three-way interaction between seeding rate, species, and environment had a significant effect on TDN concentration at the 2022-23 Garden City trials (Table 4.3). In the 2022 irrigated trial within sorghum-sudan and pearl millet, seeding rate had a significant effect on TDN concentration (Table 4.17). In sorghum-sudan, the significant difference was between the 2.22 M seeds ha^{-1} seeding rate, which had the greatest TDN concentration, and the 1.11 M and 1.48 M

seeds ha^{-1} seeding rates, which had the lowest TDN concentrations. In pearl millet, the 0.37 M seeds ha^{-1} seeding rate had a significantly greater TDN concentration than every other seeding rate except the 1.85 M seeds ha^{-1} seeding rate. There were no significant differences between species in the 2022 irrigated trial. In the 2023 irrigated trial, there were no significant differences between species in terms of TDN concentration; however, within sudangrass, a significant effect of seeding rate on TDN concentration was observed (Table 4.18). The significant difference was only between the 1.11 M seeds ha^{-1} seeding rate, the seeding rate with the greatest TDN concentration, and the 1.85 seeds ha^{-1} seeding rate, the seeding rate with the least TDN concentration. In the 2023 Garden City dryland trial, the only species in which seeding rate had a significant effect on TDN concentration was pearl millet (Table 4.19). The relationship between seeding rate and TDN concentration in pearl millet for this trial was as follows: 1.11 M seeds ha^{-1} = 1.48 M seeds ha^{-1} = 1.85 M seeds ha^{-1} ≥ 2.22 M seeds ha^{-1} ≥ 0.74 M seeds ha^{-1} ≥ 0.37 seeds ha^{-1}. There was a significant difference in TDN concentration between sudangrass (the greatest TDN concentration) and pearl millet (the lowest TDN concentration) across seeding rates in the 2023 Garden City dryland trial.

In the 2023 Hays trial, the interaction between seeding rate and species had a significant effect on TDN concentration (Table 4.5). Forage sorghum was the only species in which seeding rate did not have a significant effect on TDN concentration. In sorghum-sudan, sudangrass, and pearl millet, the highest seeding rate had the highest TDN concentration, but it was never statistically significantly higher than the TDN concentration of all other seeding rates in any of these three species, and the relationship between TDN concentration and seeding rate was not strictly linear in any of these three species (Table 4.14). There were significant differences between species across seeding rates in terms of TDN concentration in this trial. The relationship

between species and TDN concentration for the 2023 Hays trial was as follows: forage sorghum ≥ sudangrass ≥ sorghum-sudan ≥ pearl millet. When all these results for TDN concentration are considered together, although significant differences among seeding rates and species occurred for TDN concentration, no consistent trend relating to seeding rate, species, or their interaction with TDN concentration emerged.

The final forage nutritive value we evaluated was RFQ. There was no significant correlation between seeding rate and RFQ (Table 4.4). However, the three-way interaction between seeding rate, species, and environment had a significant effect on RFQ for the 2022-23 Garden City trials (Table 4.3). For the 2022 irrigated trial, seeding rate had a significant effect on RFQ in sorghum-sudan and pearl millet (Table 4.17). For sorghum-sudan, the significant difference was between the 2.22 M seeds ha^{-1} seeding rate, which had the greatest RFQ value, and the 1.11 M and 1.48 M seeds ha^{-1} seeding rates, which had the lowest RFQ values. For pearl millet, the significant difference was between the 0.37 M seeds ha^{-1} seeding rate, the seeding rate with the greatest RFQ value, and the 0.74 M and 2.22 M seeds ha^{-1} seeding rates, the seeding rates with the lowest RFQ values. There were no significant differences between species across seeding rates in terms of RFQ for the 2022 irrigated trial. For the 2023 irrigated trial, sudangrass was the only species in which seeding rate had a significant effect on RFQ (Table 4.18). The only significant difference was between the 1.11 M seeds ha^{-1} seeding rate, which had the greatest RFQ value, and the 1.48 M and 1.85 M seeds ha^{-1} seeding rates, which had the lowest RFQ values. There were no significant differences between species in terms of RFQ value for the 2023 irrigated trial. In the 2023 dryland trial, seeding rate did not have a significant effect on RFQ for any species (Table 4.19), but forage sorghum had a significantly greater RFQ value than sorghum-sudan.

In the Hays 2023 trial, sorghum-sudan and sudangrass were the only species in which seeding rate had a significant effect on RFQ (Table 4.14). In sorghum-sudan, the 1.85 M seeds ha^{-1} seeding rate had a significantly lower RFQ than the 0.37 M and 2.22 M seeds ha^{-1} seeding rates. In sudangrass, the 0.74 M seeds ha^{-1} seeding rate had a significantly lower RFQ than the 0.37 M and 1.11 M seeds ha^{-1} seeding rates. There was a significant main effect of species on RFQ value for the Hays 2023 trial (Table 4.5). The relationship between species and RFQ for this trial was as follows: pearl millet ≥ forage sorghum ≥ sudangrass ≥ sorghum-sudan (Table 4.14). Considering the totality of these results, no definitive relationships between seeding rate, species, or their interaction and RFQ could be identified. In summary, we were unable to draw any significant conclusions about the relationship between forage nutritive value and seeding rate or species based on our results.

Nutritive value per area

While the seeding rate did not consistently affect forage nutritive values, it did have a clearer impact on CP yield and TDN yield. In the 2022-23 Garden City trials, seeding rate had a significant main effect on both CP yield and TDN yield (Table 4.20). The seeding rate × species interaction, the seeding rate × environment interaction, and the three-way interaction between the three main effects did not significantly affect CP yield and TDN yield for these trials. In the Garden City trials, both CP yield and TDN yield increased as the seeding rate increased (Figure 4.1; Figure 4.2). The CP yield saw significant increases up to a seeding rate of 1.48 M seeds ha^{-1}, and the TDN yield saw significant increases up to a seeding rate of 1.85 M seeds ha^{-1}. However, during the 2023 Hays trial, the driest trial in the study, seeding rate did not have a significant effect on CP yield or TDN yield (Table 4.20).

The species × environment interaction significantly affected both CP yield and TDN yield. In both years of the irrigated trials, pearl millet generally had significantly lower CP and TDN yields than the other species in the study. In contrast, forage sorghum and sorghum-sudan generally had the greatest CP yield and TDN yield. However, in the two dryland environments, forage sorghum generally had a significantly lower CP yield and TDN yield than sorghum-sudan. Just as in the irrigated trials, pearl millet CP yield and TDN yield tended to lag significantly behind those of sorghum-sudan and sudangrass. In summary, sorghum-sudan maximized CP yield and TDN yield in both irrigated and dryland environments, whereas forage sorghum only maximized forage nutritive value per area in irrigated environments. Pearl millet tended to have significantly lower CP and TDN yields than the other species in all environments.

Correlation analysis

To this point, we have examined the relationship between the seeding rate and other variables, including the identification of any linear correlations between the seeding rate and the other variables in the study. However, our correlation analysis also revealed important correlations between other variables. The first of these relationships was that yield had a significant negative correlation with CP concentration and a weaker, yet still significant, positive correlation with NDF concentration (Table 4.4). Plant height was strongly negatively correlated with leaf-to-stem ratio. It also showed a weaker, yet still significant, positive correlation with stalk diameter. Plant height had significant correlative relationships with all forage nutritive values except crude protein. It had a strong positive correlation with NDF and ADF concentration and a weaker but still significant positive correlation with lignin concentration. Plant height showed a strong inverse correlation with RFQ and a weaker, yet still significant, negative correlation with TDN concentration. Stalk diameter exhibited these same correlations to

the forage nutritive values as plant height, except that they were all weaker correlations (barring lignin concentration, which was about equivalent to plant height's correlation with lignin concentration). This correlation suggests that increased stalk diameter was also an indicator of decreased forage quality, but not as strong an indicator as increased plant height.

Plant height was generally negatively correlated with forage quality, and it was also negatively correlated with the leaf-to-stem ratio. Consequently, the leaf-to-stem ratio was generally positively correlated with forage quality. Leaf-to-stem ratio had strong negative correlations with the fiber measures and even stronger positive correlations with TDN concentration and RFQ. Tillers per plant also had significant, but weaker, negative correlations with NDF and ADF concentration, although it did not have a significant correlation with lignin concentration. It also exhibited a significant, albeit weaker, positive correlation with RFQ, although it did not show a significant correlation with TDN. Tillers per plant also had a statistically significant positive correlation with CP concentration (leaf-to-stem ratio did not have a significant correlation with CP concentration). In general, increased leaf-to-stem ratio was a strong indicator of increased forage quality. At the same time, increased tillering was also an indicator of increased forage quality, but not as strong an indicator as increased leaf-to-stem ratio.

Not surprisingly, all the fiber measures showed strong positive correlations with one another. This result was expected because there is some overlap in what parts of the plant NDF and ADF concentrations measure (Lee, 2018). For example, lignin concentration contributes to both NDF and ADF concentrations. Also, all three fiber measures had strong negative correlations with TDN concentration and RFQ (Table 4.4). We also expected this as increased NDF, ADF, and lignin concentration are known to decrease forage quality (Benedict, 2012).

On the other hand, CP concentration had a less straightforward relationship with the other forage nutritive values. It exhibited a strong negative correlation with NDF concentration, a weaker but still significant negative correlation with ADF concentration, and a weak yet significant positive correlation with lignin concentration (Table 4.4). It also had a significant negative correlation with TDN concentration, but a significant positive correlation with RFQ.

We also conducted a correlation analysis for each species in the study to determine whether any particular species was driving the results of our correlation analysis across species. In general, the results of our across-species correlation analysis were similar to those of the analyses conducted for each individual species (Table 4.4; Table 4.21; Table 4.22; Table 4.23; Table 4.24). There were some minor differences worth discussing. While still statistically significant, pearl millet exhibited a weaker correlation between seeding rate and forage mass and between seeding rate and stalk diameter than the other species in the study. This is likely because pearl millet tillered more than the other species in the study. This increased tillering resulted in narrower forage mass differences between lower and higher seeding rates, because at lower seeding rates, pearl millet produced enough tillers to help offset the decrease in biomass caused by fewer plants in the field. We theorize that this tillering effect was also behind the weaker correlation between seeding rate and stalk diameter in pearl millet. With a more similar number of total stalks among the seeding rates for pearl millet as compared to the other species in the study, the differences in stalk diameter among seeding rates were less pronounced in pearl millet than in the other species of the study.

We identified a couple of weak, but statistically significant correlations between seeding rate and forage nutritive values in our across-species correlation analysis. These weak correlations between seeding rate and CP concentration and lignin concentration were driven by

only select species. Forage sorghum and sudangrass were the only two species that exhibited a significant negative correlation between seeding rate and CP concentration (Table 4.21; Table 4.23). Pearl millet displayed almost no correlation between seeding rate and CP concentration (Table 4.22). On the other hand, pearl millet was the only species that exhibited a significant negative correlation between seeding rate and lignin concentration. These correlation analyses, broken out by species, revealed that the weak but statistically significant negative correlations between seeding rate and CP concentration, and between seeding rate and lignin concentration, observed in the across-species analysis, were driven by only one or two species. However, just as in our across-species correlation analysis, no species exhibited statistically significant correlations between seeding rate and NDF concentration, ADF concentration, TDN concentration, or RFQ values (Table 4.4; Table 4.21; Table 4.22; Table 4.23; Table 4.24).

Economic analysis

The final results to consider are the economic impacts of changing the seeding rate for the species in the study. We used \$3.30 kg^{-1} as our baseline seed cost and \$0.12 kg^{-1} as our baseline hay price for all warm-season grass species (Ibendahl et al., 2023; Green Cover, 2024; Albert Lea Seed, 2024; USDA Agricultural Marketing Service, 2022-2024). Under baseline economic conditions, the most profitable seeding rate tested for irrigated forage sorghum was 2.22 M seeds ha^{-1} (Table 4.25). This was true for all three irrigated site-years. For dryland forage sorghum at both Garden City and Hays in 2023, 2.22 M seeds ha^{-1} was the most profitable seeding rate, but in 2024 at both locations, 1.48 M seeds ha^{-1} was the most profitable seeding rate. The year 2024 was more typical in terms of precipitation for the region than 2023.

After conducting a partial budget analysis, we performed a sensitivity analysis to determine how changes in seed cost and hay prices affected the most profitable seeding rates. For

our sensitivity analysis, we used three seed costs ($1.10, $3.30, and $5.50 kg^{-1}) and five hay prices ($0.06, $0.09, $0.12, $0.15, and $0.18 kg^{-1}). We used the partial budget returns to determine which seeding rates to conduct a sensitivity analysis for. We selected the seeding rates for the sensitivity analysis by considering a combination of which seeding rates had the greatest partial budget returns under baseline economic conditions and which seeding rates were sufficiently different to show noticeable differences in the sensitivity analysis. Using this logic, we conducted a sensitivity analysis comparing seeding rates of 2.22 M seeds ha^{-1} and 4.44 M seeds ha^{-1} for irrigated forage sorghum, because they were the two most profitable seeding rates under baseline economic conditions. At the lowest seed cost, there was an economic benefit to increasing the seeding rate for all hay prices (Table 4.26). At the medium seeding cost, the breakeven point at which increasing the seeding rate resulted in increased profitability occurred somewhere between a hay price of $0.12 kg^{-1} and $0.15 kg^{-1}, and at the highest seeding cost, it was always more profitable to plant at a seeding rate of 2.22 M seeds ha^{-1} than 4.44 M seeds ha^{-1}.

For dryland forage sorghum, we conducted a sensitivity analysis between seeding rates of 1.48 M seeds ha^{-1} and 2.22 M seeds ha^{-1} (Table 4.27). There was an economic benefit to increasing the seeding rate for all hay prices at the lowest seeding cost. At the medium seeding cost, the breakeven point at which increasing the seeding rate resulted in increased profitability occurred somewhere between a hay price of $0.12 kg^{-1} and $0.15 kg^{-1}, and at the highest seeding cost, it was always more profitable to plant at a seeding rate of 1.48 M seeds ha^{-1} than one of 2.22 M seeds ha^{-1}.

Due to their genetic similarities and the consistency in their results across the other variables in our study, we decided to combine our data for sorghum-sudan and sudangrass and conduct a joint economic analysis of the two species. Under baseline economic conditions,

irrigated sorghum-sudan and sudangrass were most profitable in 2022 at a seeding rate of 1.48 M seeds ha^{-1} and in 2023 at a seeding rate of 2.22 M seeds ha^{-1} (Table 4.28). We conducted a sensitivity analysis for these two seeding rates and found that at the low seed cost, the breakeven point for increasing the seeding rate occurred when hay prices were somewhere between \$0.06 and \$0.09 kg^{-1} (Table 4.29). For the medium seed cost, the breakeven point was between \$0.09 and \$0.12 kg^{-1}. At the highest seeding cost, it was always more profitable to plant at a rate of 1.48 M seeds ha^{-1} than at a rate of 2.22 M seeds ha^{-1}.

For dryland sorghum-sudan and sudangrass, under baseline economic conditions, 0.74 M seeds ha^{-1} was the most profitable seeding rate in Hays, and 1.85 M seeds ha^{-1} was the most profitable seeding rate in Garden City (Table 4.28). We conducted a sensitivity analysis on these two seeding rates and found that at the lowest seed cost, it was always more profitable to increase the seeding rate (Table 4.30). At the medium seed cost, the breakeven point occurred when hay prices were between \$0.09 and \$0.12 kg^{-1}. When seed costs were the highest, increasing the seeding rate was only profitable when hay prices were at their highest.

Under baseline economic conditions, irrigated pearl millet was most profitable at a seeding rate of 1.85 M seeds ha^{-1} in 2022 and 1.48 M seeds ha^{-1} in 2023 (Table 4.31). In Garden City, dryland pearl millet was most profitable at a seeding rate of 1.85 M seeds $ha^{-1,}$ and in Hays, it was most profitable at 0.74 M seeds ha^{-1}. While there was considerable variability in profitability depending on seeding rate and environment, pearl millet generally lagged behind the other three species in partial economic returns (Table 4.25; Table 4.28; Table 4.31). Its average irrigated maximum profitability was lower than the other three species in the study, and its average dryland maximum profitability was lower than sorghum-sudan and sudangrass but greater than forage sorghum.

For irrigated pearl millet, we conducted a sensitivity analysis between seeding rates of 1.11 M seeds ha^{-1} and 1.85 M seeds ha^{-1} (Table 4.32). At the low seed cost, it was always more profitable to increase the seeding rate. At the medium seed cost, the breakeven point for increasing the seeding rate occurred when hay prices were somewhere between 0.06 and 0.09 \$ kg^{-1}. At the high seed cost, the breakeven point occurred when hay prices were between \$0.09 and \$0.12 kg^{-1}. For dryland pearl millet, we conducted a sensitivity analysis between seeding rates of 0.74 M seeds ha^{-1} and 1.85 M seeds ha^{-1} because they were the two most profitable seeding rates for dryland pearl millet (Table 4.31; Table 4.33). It was not economically advantageous to increase the seeding rate under any of the economic conditions in our sensitivity analysis for dryland pearl millet.

Discussion

Our results supported our hypothesis that forage mass would be maximized at different seeding rates, depending on the species and environmental growing conditions (Table 4.7; Table 4.8; Table 4.9; Table 4.12). In six of the seven trials in the study, seeding rate had a significant effect on forage yield (Table 4.3; Table 4.5; Table 4.6). The one trial in which seeding rate did not have a statistically significant effect on forage mass yield was the 2024 irrigated forage sorghum trial (Table 4.6). However, even though the seeding rate did not have a statistically significant effect on forage yield in this single trial, there were substantial differences in forage yield between seeding rates in the trial (Table 4.9). The highest yielding seeding rate, 4.44 M seeds ha^{-1}, outyielded the lowest yielding seeding rate, 0.74 M seeds ha^{-1}, by 90%. The results of the 2024 irrigated forage sorghum seeding rate trial showed high variability, so it is possible that additional site-years of irrigated forage sorghum trials using the same seeding rates as the 2024 trial would show a significant effect of seeding rate on forage mass.

Other studies on warm-season annual forage grasses produced mixed results on whether seeding rate had a significant effect on forage mass. Snider et al. (2012) found that in three site-years, increasing seeding rate from 116,000 seeds ha^{-1} to 291,000 seeds ha^{-1} did not affect dry matter yield. However, in a fourth site-year, a seeding rate of 218,00 seeds ha^{-1} outyielded a seeding rate of 393,000 seeds ha^{-1}. Mekasha et al. (2022) found that the seeding rate significantly impacted dry matter accumulation in dual-purpose sorghum in a study that included seeding rates ranging from 0.394 M seeds ha^{-1} to 4.15 M seeds ha^{-1}. In a Brazilian study on biomass sorghum, which included plant populations of 80,000, 100,000, 120,000, and 140,000 plants ha^{-1} and row spacings of 50, 70, 90, and 110 cm, May et al. (2016) found that row spacing influenced the fresh biomass yield of sorghum significantly more than the plant population. This was because losses in plant population were compensated by tillering, and tillering was greatest in the narrowest row spacing, resulting in yield being maximized with the narrowest rows (May et al., 2016). Snider et al. (2012) also found that the narrowest rows resulted in the greatest forage mass. In a Pennsylvanian study comparing seeding rates of 200,000 seeds ha^{-1} and 300,000 seeds ha^{-1} for brachytic dwarf BMR forage sorghum silage, Elango et al. (2020) found no significant difference between seeding rates in terms of dry matter yield. These results suggest that if we used wider row spacing, which is typical in silage production, we may not have seen an effect of seeding rate on forage mass. In a non-irrigated study in Quebec, Canada, with four seeding rates of pearl millet (5, 10, 15, and 20 kg ha^{-1}) and two row spacings (18 and 36 cm), Bouchard et al. (2011) found no significant effect of seeding rate on biomass yield.

Studies on the effect of seeding rate on cool-season annual forage grasses consistently showed that seeding rate did not have a significant effect on forage yield. A study on dual-purpose winter wheat [Triticum aestivum L.], which included seeding rates of 33.6, 67.3, 100.9,

and 134.5 kg ha^{-1}, found that seeding rate did not have a significant effect on forage yield (Darapuneni et al., 2016). Studies on triticale [× Triticosecale Wittmack] and spring oat [Avena sativa L.]) planted at three different seeding rates found that seeding rate did not have a significant effect on biomass yield in either species (Obour et al., 2019; Obour et al., 2020).

One potential explanation for why our study generally showed a significant effect of seeding rate on forage mass, while other studies did not, is we tested at least six different seeding rates in every trial of our study. In contrast, most other studies only tested two to four different seeding rates. The one exception to this is Mekasha et al. (2022), which tested five seeding rates and showed a significant effect of seeding rate on forage dry matter accumulation. In the site-years where the seeding rate significantly affected forage mass, Mekasha et al. (2022) observed a plateau relationship between seeding rate and forage mass. We observed a similar plateau relationship between seeding rate and forage mass throughout our study (Table 4.8; Table 4.12). Forage yield initially increased as the seeding rate increased. However, eventually, at a seeding rate below the maximum, no further significant yield gains were achieved as the seeding rate increased. In our study and Mekasha et al. (2022), the seeding rate at which this plateau occurred varied depending on the growing season environment, as well as the species in our case, and the genetic variety in the case of Mekasha et al. (2022) (Table 4.8; Table 4.12). While there was no existing research directly comparing the four species in our study, prior research has shown that the forage yield of these species can vary significantly depending on genetic differences (Bhattarai et al., 2019; Mekasha et al., 2022). Our research aligned with the impact of genetics on forage mass, as species had a significant effect on forage yield in all trials. Specifically, pearl millet generally yielded significantly less than the other species (Table 4.3; Table 4.5; Table 4.10; Table 4.11).

Our results strongly supported our hypothesis that as seeding rate increased, stalk diameter would decrease (Table 4.4; Table 4.5; Table 4.7; Table 4.12; Table 4.13; Table 4.15; Table 4.16). This result aligned with the findings of Mekasha et al. (2022) and Snider et al. (2012). This is an important finding because Pigden and Heinrichs (1957) found that finer stems may contain less lignin, which could improve digestibility. Additionally, thick stems have higher crude fiber content than thin stems (Mowat et al., 1966). Our results support the idea that reducing stalk diameter reduces NDF, ADF, and lignin concentrations, while increasing digestibility. We found significant positive correlations between stalk diameter and fiber measures in our study, as well as significant inverse correlations between stalk diameter and TDN and RFQ (Table 4.4). While reducing stalk diameter may improve forage quality, Snider et al. (2012) reported issues with plant lodging when stalks got too thin. Although it was not an issue we encountered in our study, it is a management concern to consider when increasing the seeding rate.

Our results were less clear regarding our hypothesis that increasing the seeding rate would increase the leaf-to-stem ratio. We did not find a significant linear correlation between seeding rate and leaf-to-stem ratio in any species in the study (Table 4.21; Table 4.22; Table 4.23; Table 4.24). Either the main effect of seeding rate and/or the interaction between seeding rate and species had a significant effect on the leaf-to-stem ratio in every trial of our study, but this effect did not exhibit a consistent, discernible relationship (Table 4.3; Table 4.5; Table 4.6; Table 4.9; Table 4.12; Table 4.14; Table 4.15). The other existing research on the relationship between leaf-to-stem ratio and seeding rate did not reveal a significant relationship between the two; with the inconsistencies in our results, the nature of this relationship remains unclear (Bouchard et al., 2011).

Our results indicate a consistent inverse relationship between seeding rate and plant height (Table 4.4; Table 4.8; Table 4.9; Table 4.12). Mekasha et al. (2022) found a weak inverse correlation between plant height and seeding rate, with a correlation coefficient of –0.10 and a P-value of 0.0853. In two of the study's six site-years, a statistically significant inverse relationship was observed between seeding rate and plant height. However, in the other four site-years, the seeding rate did not have a statistically significant effect on plant height (Mekasha et al., 2022). In Snider et al. (2012), one site-year displayed an inverse relationship between plant height and seeding rate, one site-year displayed a positive relationship between plant height and seeding rate, and in the last site-year, plant height was similar across all seeding rates. While previous research provided some indication of an inverse relationship between seeding rate and plant height, our study provided strong additional evidence to confirm this relationship in forage sorghum, sorghum-sudan, sudangrass, and pearl millet.

In a study on the impacts of seeding rate in pearl millet, Bouchard et al. (2011) found a significant inverse relationship between seeding rate and number of tillers. Gerik and Neely (1987) and Lafarge et al. (2002) both found reductions in tillering as plant density increased in grain sorghum, and both studies used lower seeding rates to achieve lower plant densities, so it is reasonable to infer from their results that lower seeding rates promote tillering in grain sorghum. Our results support the idea of an inverse relationship between seeding rate and tillering (Table 4.4; Table 4.7; Table 4.9; Table 4.12). Our results indicated that pearl millet had the greatest tillering capacity among the species in our study (Table 4.10; Table 4.11; Table 4.12). Our results also indicated that more tillering occurred in irrigated than dryland environments (Table 4.10). This result was in line with Chaturvedi et al. (1981), which found increased tillering in wheat,

triticale, and barley [Hordeum vulgare L.] under irrigated conditions compared to non-irrigated conditions.

Moving to the relationship between seeding rate and forage nutritive values, our results did not support our hypothesis that increasing seeding rate would increase CP concentration. There was a relatively weak but significant negative correlation between the two in forage sorghum and sudangrass, but no significant correlation between the two in sorghum-sudan or pearl millet (Table 4.21; Table 4.22; Table 4.23; Table 4.24). In the 2022-23 Garden City trials, neither seeding rate nor any of its interactions had a significant effect on CP (Table 4.3). In the 2023 Hays trial, seeding rate had a significant effect on CP, with the two highest seeding rates having the lowest CP concentrations (Table 4.5; Table 4.7). Our results indicate that increasing the seeding rate either had no effect on CP concentration or lowered it. These results align with those of Mekasha et al. (2022) and Elango et al. (2020), which both found that the seeding rate did not affect the concentration of CP in dual-purpose sorghum and brachytic dwarf BMR forage sorghum, respectively. Studies on other species have also found that seeding rate did not affect CP concentration. Obour et al. (2020) failed to find a significant effect of seeding rate on CP concentration in triticale, and Kaur et al. (2024) did not find a significant effect of seeding rate on CP concentration in silage corn.

Our results also failed to clearly support our hypothesis that as seeding rate increased, fiber content (NDF, ADF, and lignin) would decrease. There was no significant correlation between seeding rate and NDF or ADF correlation for any species in the study (Table 4.21; Table 4.22; Table 4.23; Table 4.24). While there was a significant negative correlation of –0.26 between seeding rate and lignin concentration in pearl millet, there were no significant correlative relationship between seeding rate and lignin concentration in any of the other species. Seeding

rate only had a significant effect on lignin concentration within a handful of species in a handful of environments (Table 4.4; Table 4.14; Table 4.17; Table 4.18; Table 4.19). Even in instances where the seeding rate had a significant effect on lignin concentration, there was no clear relationship. Generally, higher seeding rates would result in lower lignin concentrations, but there were numerous exceptions to this trend. Our results contradict those of Mekasha et al. (2022), which found that increasing the seeding rate significantly decreased NDF, ADF, and acid detergent lignin. On the other hand, Bouchard et al. (2011) found that seeding rate generally did not affect plant ADF and NDF concentrations in pearl millet. Research on the impact of seeding rate on triticale and silage corn found that increasing seeding rates increased NDF and ADF concentration (Obour et al., 2020; Kaur et al., 2024).

The final two forage nutritive values we analyzed were TDN and RFQ. We did not find a significant correlation between seeding rate and TDN or RFQ for any species in the study (Table 4.21; Table 4.22; Table 4.23; Table 4.24). While in certain environments for certain species, seeding rate had a significant effect on TDN and RFQ, we were unable to draw overarching conclusions on the relationship between seeding rate and TDN and RFQ based on our results (Table 4.4; Table 4.14; Table 4.17; Table 4.18; Table 4.19). In summary, we did not find evidence to suggest that increasing seeding rate improved total forage energy, intake, or digestibility.

There is no existing research on the effect of seeding rate on TDN and RFQ in annual forage grasses; however, other studies have investigated the impact of seeding rate on different forage digestibility and energy measures. Mekasha et al. (2022) found a significant direct relationship between seeding rate and in vitro organic matter digestibility, suggesting that increasing the seeding rate improves the digestibility of forage sorghum. In other species, the relationship between seeding rate and digestibility was different. Obour et al. (2020) found that in

triticale, in vitro dry matter digestibility decreased as the seeding rate increased. In contrast, Kaur et al. (2024) did not find a consistent relationship between seeding rate and in vitro dry matter digestibility in silage corn. Elango et al. (2020) found that seeding rate did not have a significant effect on net energy lactation (a measure of forage energy) in brachytic dwarf BMR forage sorghum.

Overall, our results showed no clear relationship between seeding rate and forage nutritive values. For CP concentration and forage energy, our results aligned with existing research that also failed to establish clear relationships between seeding rate and CP concentration or forage energy (Mekasha et al., 2022; Elango et al., 2020; Obour et al., 2020; Kaur et al., 2024). However, our results regarding the relationship between seeding rate, fiber concentrations, and forage digestibility were not entirely in line with existing prior research. Prior research has provided conflicting answers to the question of how seeding rate impacts forage nutritive values, and the closest our research comes to answering that question is by suggesting that there may not be an overarching relationship between the two at all.

The economic approach we took to analyze the relationship between seeding rate and profitability was a novel approach for the species in this study. However, our results shared some similarities with those of Bourgault et al. (2024), who originally applied this method of economic analysis to lentil yields in Montana. In both our study and Bourgault et al. (2024), the economic optimum seeding rate varied depending on the growing environment (Table 4.25; Table 4.28; Table 4.31). Bourgault et al. (2024) theorized that the productivity of the growing environment, particularly water availability, was the cause of these differences. Our results support this theory, as our irrigated and wetter dryland environments consistently had higher economic optimum seeding rates than our low-water dryland environments (Table 4.25; Table 4.28; Table 4.31). One

difference between our economic analysis and that of Bourgault et al. (2024) was that we analyzed multiple species, whereas they analyzed just one. Consequently, we also observed differences in the economic optimum seeding rate based on species, as well as the growing environment. Generally, pearl millet had lower economic optimum seeding rates than the other species (Table 4.25; Table 4.28; Table 4.31). We believe this is because pearl millet was less responsive in terms of forage mass to seeding rate increases than the other species in the study (Table 4.12). We theorize that this reduced responsivity is because pearl millet tillered more than the other species in the study (Table 4.10; Table 4.11). This decreased forage mass responsivity, along with its increased tillering capacity, suggests that the reason pearl millet generally had a lower economic optimum seeding rate than the other species in the study was because at lower seeding rates, pearl millet produced enough tillers to compensate well for the reduction in plant population caused by a lower seeding rate. Thus, the increased cost from increasing the seeding rate was not offset by a large enough increase in forage mass (as was generally seen in the three other species we studied), resulting in a lower economic optimum seeding rate. In general, regardless of seeding rate, pearl millet tended to have lower partial economic returns than the other three species in the study due to its lower forage mass (Table 4.11; Table 4.12; Table 4.25; Table 4.28; Table 4.31).

Conclusion

This study supported our hypotheses that increasing seeding rate of summer annual forage grasses would result in smaller stalk diameters and that the agronomic optimum seeding rate would vary depending on the species and growing environment. However, this study did not support our hypotheses that increasing the seeding rate of summer annual forage grasses would result in greater leaf-to-stem ratios and enhanced forage quality. Our results showed that

decreased plant height and stalk diameter, along with increased leaf-to-stem ratio and tillering, were generally better indicators of low fiber, high energy, and high digestibility forage than seeding rate was. Increasing the seeding rate tended to decrease plant height, tillering, and stalk diameter, but had no discernible effect on the leaf-to-stem ratio.

Our results generally showed a plateau relationship between seeding rate and forage mass, where forage mass initially rose with increased seeding rate but eventually reached a point at which further increases in seeding rates resulted in no additional yield gains. The seeding rate at which this yield plateau occurred varied depending on species and growing environment. However, it tended to occur at lower seeding rates in pearl millet and drier environments. Similarly, the economic optimum seeding rate also varied depending on species and environment, with wetter environments tending to support higher economic optimum seeding rate. Pearl millet was the least responsive to seeding rate increases, and least profitable species in this study. Both forage mass and profitability had a complex relationship with seeding rate, which varied significantly depending on environmental and economic conditions. We advise producers to consider the amount of available moisture, the cost of seed, and the value of hay when selecting a seeding rate for a summer annual forage grass. Under irrigated conditions to maximize profitability, we generally recommend a seeding rate of 2.22 M seeds ha^{-1} for forage sorghum, 1.48-2.22 M seeds ha^{-1} for sorghum-sudan and sudangrass, and 1.48-1.85 M seeds ha^{-1} for pearl millet. Under dryland conditions in the semi-arid Great Plains, to maximize profitability, we generally recommend a seeding rate of 1.48-2.22 M seeds ha^{-1} for forage sorghum, 0.74-1.85 M seeds ha^{-1} for sorghum-sudan and sudangrass, and 0.74 M seeds ha^{-1} for pearl millet.

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Figures

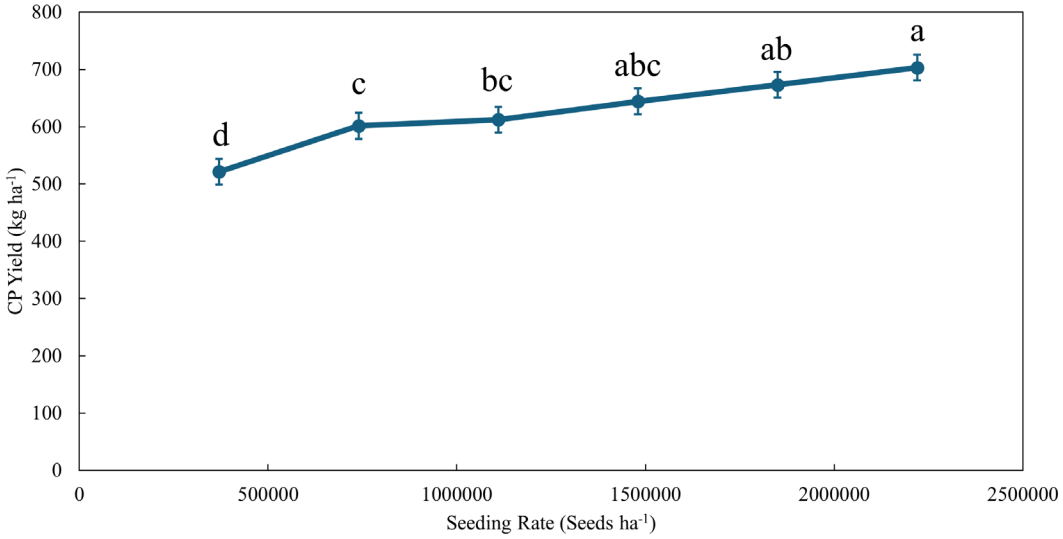

Figure 4.1. CP yield by seeding rate across species and environment for Garden City, KS 2022-23 trials. Error bars represent the standard error of the mean. Means with the same letter are not significantly different (α =0.05).

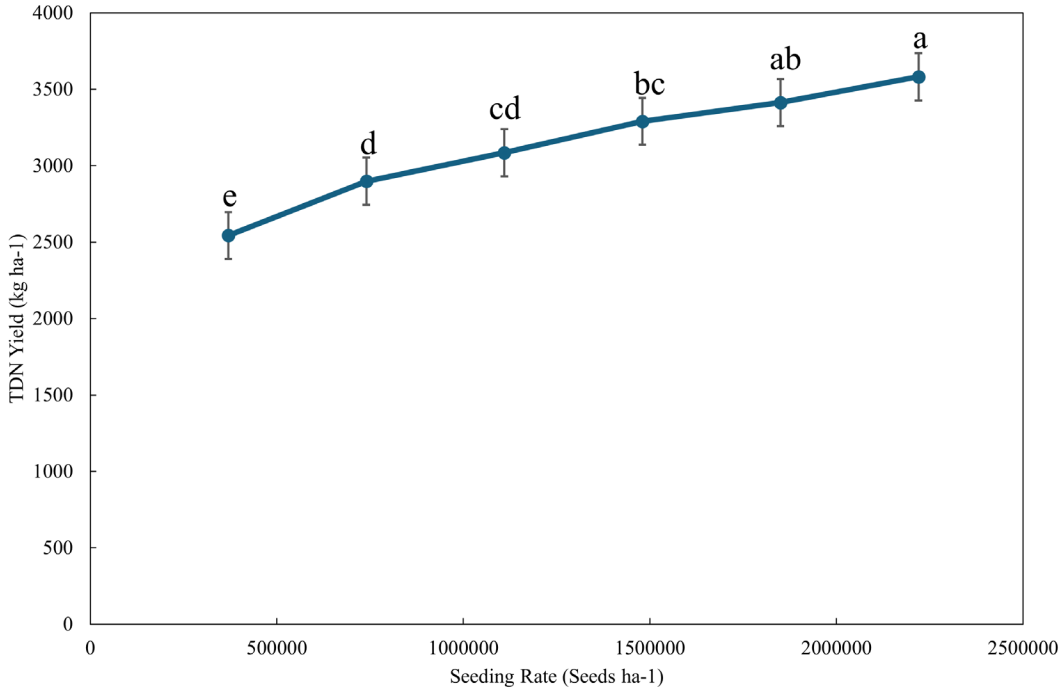

Figure 4.2. TDN Yield by seeding rate across species and environment for Garden City, KS 2022-23 trials. Error bars represent the standard error of the mean. Means with the same letter are not significantly different (α =0.05).

Tables

Table 4.1. Variety name, seed weight, and pure live seed percentage of species in study.

Species	Variety name	Seed Weight	Pure Live Seed
		seeds kg^{-1}	%
Forage Sorghum	Nutri-Cane II	52110	84.15
Sorghum-Sudan	Sweetleaf II	50917	84.15
Sudangrass	Trudan 8	63288	83.30
Pearl Millet	Millex 32	125073	83.30

Table 4.2. Monthly precipitation in 2022, 2023, 2024, and the 60-yr average for Garden City and Hays, KS. (Kansas State University, 2024; National Oceanic Atmospheric Administration, 2024)

	Garden City				Hays		
	2022	2023	2024	60-yr ave.[a]	2023	2024	60-yr ave.
Month	mm						
Jan.	12	3	21	11	23	19	13
Feb.	0	15	10	13	7	32	17
Mar.	7	1	14	29	6	10	40
Apr.	10	57	4	40	18	15	52
May	55	111	49	78	79	46	84
Jun.	32	130	71	74	81	111	80
Jul.	54	97	121	73	57	77	91
Aug.	10	54	76	64	95	105	78
Sept.	15	47	28	37	17	22	51
Oct.	1	21	3	29	19	6	39
Nov.	3	5	106	16	11	99	24
Dec.	1	38	0	14	45	1	18
Annual	199	578	503	477	459	543	585

[a]60-yr averages from 1964-2024

Table 4.3. Type III test of fixed effects for forage mass (FM), establishment rate (Est), plant height (height), tillers per plant (tillers), leaf-to-stem ratio (LSR), stalk diameter (SD), crude protein (CP), neutral-detergent fiber (NDF), acid-detergent fiber (ADF), lignin (L), total digestible nutrients (TDN), and relative feed quality (RFQ) in Garden City, KS 2022-23 trials.

Fixed Effects	FM	Est	Height	Tillers	LSR	SD	CP	NDF	ADF	L	TDN	RFQ
Species (S)	<0.0001	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	0.0121	0.1723	0.8397	0.2350	0.5442	<0.0001
Seeding Rate (SR)	<0.0001	0.0228	<0.0001	<0.0001	0.0009	<0.0001	0.0967	0.0205	0.1134	<0.0001	0.1382	<0.0001
Environment (E)	0.7542	0.0005	<0.0001	0.0004	0.0452	0.1200	<0.0001	0.0237	0.0021	<0.0001	0.0001	0.0001
S x SR	0.0893	0.1592	0.0808	<0.0001	0.0533	<0.0001	0.4253	0.0503	0.3155	0.0047	0.6545	0.0553
S x E	<0.0001	0.0014	<0.0001	<0.0001	<0.0001	0.0002	0.0075	0.0135	0.6355	0.0945	0.3646	0.0192
SR x E	0.4848	0.3681	0.1512	<0.0001	0.6181	0.0051	0.2451	0.1422	0.3236	<0.0001	0.0078	<0.0001
S x SR x E	0.2486	0.6277	0.9092	0.4573	0.2314	0.5250	0.0799	0.0317	0.0408	0.0023	<0.0001	0.0026

Table 4.4. Pearson correlation coefficients among seeding rate (SR), plant population (Pop), forage mass (FM), plant height (height), tillers, leaf-to-stem ratio (LSR), stalk diameter (SD), crude protein (CP), neutral-detergent fiber (NDF), acid-detergent fiber (ADF), lignin, total digestible nutrients (TDN), and relative feed quality (RFQ) across all trials and species in 2022-23 (n=384).[a]

	SR	Pop	FM	Height	Tillers	LSR	SD	CP	NDF	ADF	Lignin	TDN
Pop	**0.820**											
FM	**0.404**	**0.449**										
Height	**-0.225**	**-0.118**	**0.129**									
Tillers	**-0.452**	**-0.638**	**-0.415**	0.081								
LSR	0.071	-0.047	**0.123**	**-0.457**	-0.021							
SD	**-0.484**	**-0.365**	**-0.235**	**0.232**	**0.150**	**-0.344**						
CP	**-0.130**	**-0.256**	**-0.298**	-0.063	**0.228**	-0.056	0.081					
NDF	0.039	**0.235**	**0.197**	**0.454**	**-0.216**	**-0.411**	**0.161**	**-0.439**				
ADF	0.016	**0.198**	0.069	**0.455**	**-0.146**	**-0.502**	**0.197**	**-0.238**	**0.905**			
Lignin	**-0.135**	0.036	-0.069	**0.224**	-0.042	**-0.472**	**0.240**	**0.146**	**0.505**	**0.695**		
TDN	0.031	**-0.103**	**0.106**	**-0.315**	0.038	**0.530**	**-0.237**	**-0.197**	**-0.626**	**-0.858**	**-0.827**	
RFQ	-0.016	**-0.220**	**-0.114**	**-0.446**	**0.182**	**0.506**	**-0.216**	**0.248**	**-0.949**	**-0.973**	**-0.683**	**0.830**

[a]Values in bold are statistically significant (α =0.05).

Table 4.5. Type III test of fixed effects for forage mass (FM), establishment rate (Est), plant height (height), tillers per plant (tillers), leaf-to-stem ratio (LSR), stalk diameter (SD), crude protein (CP), neutral-detergent fiber (NDF), acid-detergent fiber (ADF), lignin (L), total digestible nutrients (TDN), and relative feed quality (RFQ) for Hays, KS 2023 trial.

Fixed Effects	FM	Est	Height	Tillers	LSR	SD	CP	NDF	ADF	L	TDN	RFQ
Species (S)	<0.0001	<0.0001	0.0033	<0.0001	<0.0001	0.0494	<0.0001	<0.0001	0.0072	<0.0001	<0.0001	<0.0001
Seeding Rate (SR)	0.0402	<0.0001	0.1312	<0.0001	0.4486	0.0134	0.0335	0.0176	0.0234	0.0023	0.0234	0.0003
S x SR	0.6939	0.4401	0.2685	0.0969	0.0009	0.1164	0.9886	0.5364	0.4144	0.0014	0.0286	0.081

Table 4.6. Type III test of fixed effects for forage mass (FM), establishment rate, plant height (height), tillers per plant (tillers), leaf-to-stem ratio (LSR) and stalk diameter for 2024 forage sorghum seeding rate trials in Garden City and Hays, KS.

Trials and Fixed Effects	FM	Establishment	Height	Tillers	LSR	Stalk Diameter
	P>F					
Dryland Trials						
Seeding Rate (SR)	<0.0001	<0.0001	<0.0001	0.0473	<0.0001	------
Location (L)	0.0128	0.1862	0.0010	0.3044	0.6949	------
SR x L	0.6809	0.0676	0.8219	0.1085	<0.0001	------
Irrigated Trials						
Seeding Rate (SR)	0.1426	0.0035	<0.0001	0.0047	0.0142	------
Garden City Trials						
Seeding Rate (SR)	------	------	------	------	------	<0.0001
Irrigation (I)	------	------	------	------	------	0.0006
SR x I	------	------	------	------	------	0.4767

Table 4.7. Forage mass (FM), establishment (Est), plant height (height), tillers per plant (tillers), stalk diameter (SD), crude protein (CP), neutral-detergent fiber (NDF), and acid-detergent fiber (ADF) by seeding rate in Hays, KS 2023.

Seeding Rate	FM	Est	Height	Tillers	SD	CP	NDF	ADF
seeds ha^{-1}	kg ha^{-1}	%	m	tillers	mm	---------- % ----------		
370,000	4706 c	92.9 a	1.73	1.90 a	9.58 a	12.5 a	50.6 b	32.1 b
740,000	6059 ab	85.4 a	1.87	0.54 b	9.42 a	11.3 ab	52.6 a	33.4 a
1,110,000	5023 bc	61.3 b	1.74	0.96 b	8.91 ab	12.3 a	50.4 b	31.9 b
1,480,000	5533 abc	60.5 b	1.72	0.61 b	8.82 ab	12.4 a	50.5 b	32.5 ab
1,850,000	6100 ab	51.8 b	1.73	0.74 b	8.94 ab	11.0 b	52.6 a	33.6 a
2,220,000	6334 a	54.6 b	1.52	1.00 b	8.25 b	11.0 b	51.1 ab	32.5 ab

[a]Means followed by the same lower-case letter within a species are not significantly different (α =0.05). If there are not any lower-case letters present, means are not significantly different.

Table 4.8. Forage mass, establishment, plant height (height), and tillers per plant (tillers), by seeding rate and location for 2024 forage sorghum seeding rate dryland trials in Garden City and Hays, KS.

Factor	Forage Mass	Establishment	Height	Tillers
	kg ha^{-1}	%	m	tillers
Seeding Rate (seeds ha^{-1})				
370,000	4434 c[a]	100 a	2.01 a	0.28 a
740,000	5966 bc	94.2 ab	2.05 a	0.28 a
1,480,000	7809 a	81.4 abc	1.95 a	0.16 ab
2,220,000	7229 ab	75.3 bc	1.80 ab	0.01 b
2,960,000	8027 a	72.2 c	1.81 ab	0.01 b
3,700,000	7265 ab	65.6 c	1.57 b	0.00 b
4,440,000	8198 a	61.7 c	1.66 b	0.00 b
Location				
Garden City	5818 b	83.7	1.52 a	0.14
Hays	8161 a	74.0	2.15 a	0.07

[a]Means within a factor followed by the same lower-case letter are not significantly different (α =0.05).
If there are not any lower-case letters present, means are not significantly different.

Table 4.9. Forage mass, establishment, plant height (height), tillers per plant (tillers), and leaf-to-stem ratio by seeding rate for the 2024 irrigated forage sorghum trial in Garden City, KS.

Seeding Rate	Forage Mass	Establishment	Height	Tillers	Leaf-to-Stem Ratio
seeds ha^{-1}	kg ha^{-1}	%	m	Tillers	
370,000	7991	100 a[a]	2.37 a	1.08 a	0.082 b
740,000	6470	91.8 ab	2.26 ab	0.34 ab	0.104 ab
1,480,000	8024	67.8 b	2.17 bc	0.34 ab	0.108 ab
2,220,000	11109	62.7 b	2.03 cde	0.07 b	0.111 a
2,960,000	10536	68.7 b	2.11 bcd	0.00 b	0.118 a
3,700,000	9494	59.6 b	2.01 de	0.06 b	0.114 a
4,440,000	12351	67.3 b	1.92 e	0.00 b	0.114 a

[a]Means followed by the same lower-case letter are not significantly different (α =0.05). If there are not any lower-case letters present, means are not significantly different.

Table 4.10. Forage mass (FM), establishment (Est), plant height (height), tillers per plant (tillers), leaf-to-stem ratio (LSR), and stalk diameter (SD) by species within an environment in Garden City, KS 2022-23.

Environment	Species	FM	Est	Height	Tillers	LSR	SD
		kg ha^{-1}	%	m	Tillers		mm
2022 Irrigated	Forage Sorghum	5634 a[a]	86.2 a	1.99 b	0.37 c	0.191 a	10.7 a
	Sorghum-Sudan	5528 a	81.1 a	2.49 a	0.51 c	0.179 ab	9.70 b
	Sudangrass	5312 a	76.1 a	2.43 a	0.83 b	0.164 b	9.31 b
	Pearl Millet	4557 b	65.2 b	1.98 b	1.61 a	0.161 b	9.46 b
	Mean	5258	77.1 C[b]	2.22 A	0.83 A	0.174	9.79
2023 Dryland	Forage Sorghum	4642 b	91.9	1.68 c	0.25 b	0.158 b	11.8 a
	Sorghum-Sudan	6133 a	93.8	2.01 a	0.34 b	0.196 a	10.7 b
	Sudangrass	5790 a	92.6	1.84 b	0.47 ab	0.187 a	9.08 c
	Pearl Millet	4957 b	90.4	1.83 b	0.57 a	0.162 b	10.8 b
	Mean	5380	92.3 A	1.84 B	0.41 B	0.176	10.6
2023 Irrigated	Forage Sorghum	5767 a	95.0 a	2.33 b	0.30 b	0.137 b	11.2 a
	Sorghum-Sudan	5823 a	90.7 ab	2.44 a	0.53 b	0.171 a	10.1 b
	Sudangrass	5234 b	81.1 bc	2.28 bc	0.75 b	0.138 b	9.34 c
	Pearl Millet	4954 b	73.1 c	2.20 c	1.35 a	0.173 a	11.0 a
	Mean	5444	85.0 B	2.31 A	0.73 A	0.154	10.4

[a]Species means followed by the same lower-case letter within a species are not significantly different (α =0.05). If there are not any lower-case letters present, means are not significantly different.
[b]Environment means followed by the same upper-case letter within a column are not significantly different (α =0.05). If there are not any upper-case letters present, means are not significantly different.

Table 4.11. Forage mass, establishment (Est), plant height (height), tillers per plant (tillers), stalk diameter (SD), crude protein (CP), neutral-detergent fiber (NDF), and acid-detergent fiber (ADF) by species in Hays, KS 2023.

Species	FM	Est	Height	Tillers	SD	CP	NDF	ADF
	kg ha^{-1}	%	m		mm		——— % ———	
Forage Sorghum	5658 a[a]	81.4 a	1.50 b	0.44 b	9.38 a	9.81 c	51.5 a	32.4 ab
Sorghum-Sudan	6767 a	82.5 a	1.85 a	0.39 b	9.01 ab	11.3 b	53.0 a	33.5 a
Sudangrass	5976 a	74.2 a	1.75 ab	0.50 b	8.50 b	10.7 bc	52.4 a	32.9 ab
Pearl Millet	4108 b	32.8 b	1.76 a	2.50 a	9.05 ab	15.2 a	48.3 b	31.9 b

[a]Means followed by the same lower-case letter within a species are not significantly different (α =0.05). If there are not any lower-case letters present, means are not significantly different.

Table 4.12. Forage mass, plant height (height), tillers per plant (tillers), leaf-to-stem ratio (LSR), and stalk diameter by seeding rate within a species in Garden City, KS 2022-23.

Species	Seeding Rate	Forage Mass	Height	Tillers	LSR	Stalk Diameter
	seeds ha^{-1}	kg ha^{-1}	m	tillers		mm
Forage Sorghum	370,000	4377 c[a]	2.18 a	0.92 a	0.159	13.5 a
	740,000	4932 bc	2.02 b	0.29 b	0.159	12.4 ab
	1,110,000	5279 b	2.03 ab	0.21 b	0.151	11.8 b
	1,480,000	5466 b	1.95 b	0.17 b	0.154	10.3 c
	1,850,000	5600 b	1.93 b	0.15 b	0.168	9.97 c
	2,220,000	6432 a	1.88 b	0.08 b	0.178	9.40 c
	Mean	5348 B[b]	2.00 C	0.30 C	0.162 B	11.2 A
Sorghum-Sudan	370,000	4443 c	2.46 a	1.29 a	0.156 b	12.6 a
	740,000	5563 b	2.47 a	0.53 b	0.180 ab	11.2 b
	1,110,000	5611 b	2.32 b	0.39 bc	0.186 ab	9.89 c
	1,480,000	6296 ab	2.26 bc	0.33 bc	0.175 b	9.76 cd
	1,850,000	6528 a	2.21 bc	0.16 bc	0.210 a	8.83 de
	2,220,000	6528 a	2.17 c	0.07 c	0.182 ab	8.67 e
	Mean	5828 A	2.31 A	0.46 C	0.182 A	10.2 B
Sudangrass	370,000	4433 c	2.31 a	2.28 a	0.150	10.4 a
	740,000	4987 bc	2.27 ab	0.89 b	0.153	9.77 ab
	1,110,000	5407 b	2.22 ab	0.55 bc	0.164	9.03 bc
	1,480,000	5607 ab	2.17 bc	0.16 cd	0.157	9.05 bc

	1,850,000	5879 ab	2.07 c	0.17 cd	0.171	8.71 c
	2,220,000	6356 a	2.06 c	0.05 d	0.184	8.55 c
	Mean	5445 B	2.18 B	0.68 B	0.163 B	9.24 C
Pearl Millet	370,000	4185 b	2.07 a	3.69 a	0.163	11.6 a
	740,000	4464 b	2.05 ab	1.61 b	0.153	10.6 ab
	1,110,000	4710 ab	2.02 ab	0.66 c	0.162	10.3 b
	1,480,000	5200 a	1.99 ab	0.69 bc	0.183	10.5 ab
	1,850,000	5228 a	1.94 b	0.12 c	0.171	9.93 b
	2,220,000	5148 a	1.94 b	0.29 c	0.162	9.71 b
	Mean	4823 C	2.00 C	1.17 A	0.166 B	10.4 B

[a]Seeding rate means followed by the same lower-case letter within a species are not significantly different (α =0.05). If there are not any lower-case letters present, means are not significantly different.

[b]Species means followed by the same upper-case letter within a column are not significantly different (α =0.05).

Table 4.13. Tillers per plant (tillers) and stalk diameter by seeding rate within an environment in Garden City, KS 2022-23.

Environment	Seeding Rate	Tillers	Stalk Diameter
	Seeds ha^{-1}		mm
2022 Irrigated	370,000	2.50 a[a]	11.5 a
	740,000	1.16 b	10.8 a
	1,110,000	0.61 c	9.71 b
	1,480,000	0.31 cd	9.37 bc
	1,850,000	0.20 d	8.79 bc
	2,220,000	0.19 d	8.55 c
	Mean	0.83 A[b]	9.79
2023 Dryland	370,000	1.31 a	11.7 a
	740,000	0.49 b	11.0 ab
	1,110,000	0.23 bc	10.6 bc
	1,480,000	0.22 bc	10.6 bc
	1,850,000	0.12 c	9.94 bc
	2,220,000	0.09 c	9.65 c
	Mean	0.41 B	10.6
2023 Irrigated	370,000	2.33 a	12.9 a
	740,000	0.84 b	11.1 b
	1,110,000	0.53 bc	10.4 bc
	1,480,000	0.47 bc	9.75 cd

1,850,000	0.13 c	9.35 d
2,220,000	0.09 c	9.04 d
Mean	0.73 A	10.4

[a]Seeding rate means followed by the same lower-case letter within a species are not significantly different (α =0.05).
[b]Environment means followed by the same upper-case letter within a column are not significantly different (α =0.05). If there are not any upper-case letters present, means are not significantly different.

Table 4.14. Leaf-to-stem ratio (LSR), lignin, total digestible nutrients (TDN), and relative feed quality (RFQ) by seeding rate within a species in Hays, KS 2023.

Species	Seeding Rate	LSR	Lignin	TDN	RFQ
	Seeds ha^{-1}		----------%----------		
Forage Sorghum	370,000	0.303 ab[a]	2.77	63.9	124
	740,000	0.271 b	2.99	63.2	118
	1,110,000	0.301 ab	2.90	63.5	121
	1,480,000	0.282 b	3.01	63.5	120
	1,850,000	0.372 ab	2.84	63.0	120
	2,220,000	0.443 a	2.82	63.0	118
	Mean	0.322 A[b]	2.89 B	63.4 A	120 AB
Sorghum-Sudan	370,000	0.304 a	3.32 ab	62.7 ab	118 a
	740,000	0.273 ab	3.31 ab	62.7 ab	116 ab
	1,110,000	0.317 a	3.46 ab	62.6 ab	116 ab
	1,480,000	0.302 a	3.51 a	61.6 ab	116 ab
	1,850,000	0.180 c	3.71 a	60.3 b	106 b
	2,220,000	0.233 bc	3.02 b	63.0 a	118 a
	Mean	0.268 B	3.39 A	62.1 BC	115 C
Sudangrass	370,000	0.278	3.23 b	63.4 a	123 a
	740,000	0.231	3.97 a	61.2 b	108 b
	1,110,000	0.287	3.15 b	63.7 a	124 a

	1,480,000	0.294	3.36 ab	62.7 ab	119 ab
	1,850,000	0.265	3.38 ab	62.5 ab	114 ab
	2,220,000	0.267	3.37 ab	63.4 a	116 ab
	Mean	0.270 B	3.41 A	62.8 AB	117 BC
Pearl Millet	370,000	0.251 a	3.31	61.0 bc	122
	740,000	0.238 ab	3.41	61.9 ab	121
	1,110,000	0.231 ab	3.39	61.3 abc	128
	1,480,000	0.222 ab	3.32	60.8 c	127
	1,850,000	0.242 a	3.28	61.4 abc	120
	2,220,000	0.199 b	3.25	62.0 a	129
	Mean	0.231 C	3.32 A	61.4 C	125 A

[a]Seeding rate means followed by the same lower-case letter within a species are not significantly different (α =0.05). If there are not any lower-case letters present, means are not significantly different.
[b]Species means followed by the same upper-case letter within a column are not significantly different (α =0.05). If there are not any upper-case letters present, means are not significantly different.

Table 4.15. Leaf-to-stem ratio by seeding rate within a location for 2024 forage sorghum seeding rate dryland trials in Garden City and Hays, KS.

Seeding Rate (seeds ha^{-1})	Garden City	Hays
370,000	0.101 c[a]	0.175 b
740,000	0.151 bc	0.175 b
1,480,000	0.226 ab	0.186 b
2,220,000	0.149 bc	0.207 ab
2,960,000	0.295 a	0.192 b
3,700,000	0.228 ab	0.254 a
4,440,000	0.266 a	0.174 b
Mean	0.202[b]	0.195

[a]Means followed by the same lower-case letter within a location are not significantly different (α =0.05).
[b]There was no significant difference between the Garden City and Hays location means (α =0.05).

Table 4.16. Stalk diameter by seeding rate and irrigation for 2024 forage sorghum seeding rate trials in Garden City, KS.

Factor	Stalk Diameter
Seeding Rate (seeds ha^{-1})	mm
370,000	17.1 a
740,000	13.9 b
1,480,000	10.6 cd
2,220,000	11.4 c
2,960,000	9.78 cd
3,700,000	9.03 d
4,440,000	8.60 d
Irrigation	
Irrigated	12.7 a
Dryland	10.3 b

[a]Means within a factor followed by different lower-case

Table 4.17. **Crude protein (CP), neutral-detergent fiber (NDF), acid-detergent fiber (ADF), lignin, total digestible nutrients (TDN), and relative feed quality (RFQ) by seeding rate within a species for the 2022 irrigated trial in Garden City, KS.**

Species	Seeding Rate	CP	NDF	ADF	Lignin	TDN	RFQ
	Seeds ha^{-1}	%					
Forage							
Sorghum	370,000	13.3	57.6	37.7	4.05	57.2	96.9
	740,000	13.0	57.7	38.0	4.08	57.5	97.4
	1,110,000	12.2	58.1	37.8	4.11	57.8	97.2
	1,480,000	12.1	57.3	38.0	4.13	57.6	98.0
	1,850,000	13	58.2	38.3	4.06	57.1	95.8
	2,220,000	12.3	57.5	37.1	4.02	58.6	99.5
	Mean	12.7[b]	57.7	37.8	4.07	57.6	97.5
Sorghum-Sudan	370,000	11.7	57.5 ab[a]	38.0 abc	3.95 ab	58.3 ab	99.0 ab
	740,000	12.5	58.0 ab	38.1 abc	4.17 ab	57.9 ab	97.6 ab
	1,110,000	12.2	60.4 a	40.0 a	4.45 a	56.9 b	91.9 b
	1,480,000	11.8	60.3 a	39.9 ab	4.44 a	56.4 b	91.2 b
	1,850,000	12.3	56.6 b	37.2 bc	4.00 ab	58.1 ab	100 ab
	2,220,000	11.3	55.8 b	36.3 c	3.82 b	59.8 a	105 a
	Mean	12.0	58.1	38.2	4.14	57.9	97.4

Sudangrass	370,000	13.9	57.4	37.9	4.13	57.5	97.8
	740,000	14.2	56.7	38.7	3.88	56.1	96.9
	1,110,000	12.5	57.9	38.4	4.14	57.7	97.5
	1,480,000	13.2	58.9	39.0	4.27	56.8	94.2
	1,850,000	11.9	55.1	35.8	3.55	59.7	106
	2,220,000	12.8	58.3	38.9	4.23	56.7	95.0
	Mean	13.1	57.4	38.1	4.03	57.4	97.9
Pearl Millet	370,000	10.5	56.3	36.0 b	3.71	60.2 a	105 a
	740,000	13.1	58.9	38.8 ab	4.24	56.6 b	93.9 b
	1,110,000	12.7	57.7	38.4 ab	4.19	57.1 b	96.6 ab
	1,480,000	13.9	56.9	38.1 ab	3.96	57.1 b	97.9 ab
	1,850,000	12.3	57.2	37.1 ab	3.88	58.6 ab	100 ab
	2,220,000	13.0	58.7	39.4 a	4.16	56.4 b	94.2 b
	Mean	12.6	57.6	38.0	4.02	57.7	97.9

[a]Seeding rate means followed by the same lower-case letter within a species are not significantly different ($\alpha = 0.05$). If there are not any lower-case letters present, means are not significantly different.
[b]There were no significant differences between species for any of the forage nutritive variables in the 2022 irrigated trial at Garden City.

Table 4.18. Crude protein (CP), neutral-detergent fiber (NDF), acid-detergent fiber (ADF), lignin, total digestible nutrients (TDN), and relative feed quality (RFQ) by seeding rate within a species for the 2023 irrigated trial in Garden City, KS.

Species	Seeding Rate	CP	NDF	ADF	Lignin	TDN	RFQ
	Seeds ha^{-1}			%			
Forage							
Sorghum	370,000	10.0	60.2	38.8	4.02	58.3	94.8
	740,000	11.1	57.0	37.1	3.81	59.4	102
	1,110,000	10.8	56.0	36.6	4.02	59.4	104
	1,480,000	10.7	57.8	37.5	3.93	59.3	101
	1,850,000	10.0	55.5	35.9	3.59	60.5	107
	2,220,000	10.2	57.1	37.6	3.97	58.7	101
	Mean	10.5[b]	57.2	37.2	3.89	59.3	101
Sorghum-Sudan	370,000	10.4	54.5	35.8	3.65	60.2	108
	740,000	10.4	58.1	37.8	3.97	58.9	99.1
	1,110,000	9.82	56.5	36.8	3.56	60.2	104
	1,480,000	10.3	57.4	36.7	3.60	60.2	103
	1,850,000	10.6	55.0	35.9	3.65	59.7	106
	2,220,000	10.2	57.4	37.2	3.80	58.8	100
	Mean	10.3	56.5	36.7	3.71	59.7	103
Sudangrass	370,000	11.0	55.9 ab[a]	35.9 abc	3.69	60.5 ab	106 ab

	740,000	11.1	54.6 ab	35.5 bc	3.48	60.1 ab	108. ab
	1,110,000	12.1	52.8 b	34.2 c	3.47	61.0 a	113 a
	1,480,000	9.33	59.8 a	39.4 a	4.29	58.2 ab	95.0 b
	1,850,000	10.4	58.2 ab	38.7 ab	4.29	57.7 b	97.0 b
	2,220,000	10.3	56.0 ab	36.5 abc	3.75	59.7 ab	104 ab
	Mean	10.7	56.2	36.7	3.83	59.5	104
Pearl Millet	370,000	10.8	57.0	37.4	3.95	58.9	101
	740,000	9.37	58.1	37.7	4.07	59.2	100
	1,110,000	10.1	58.5	37.0	3.74	59.9	100
	1,480,000	10.2	56.5	36.8	3.84	59.8	104
	1,850,000	9.53	58.7	37.9	3.92	59.3	98.7
	2,220,000	11.2	53.9	35.2	3.50	61.0	111
	Mean	10.2	57.1	37.0	3.83	59.7	103

[a]Seeding rate means followed by the same lower-case letter within a species are not significantly different (α =0.05). If there are not any lower-case letters present, means are not significantly different.
[b]There were no significant differences between species for any of the forage nutritive variables in the 2023 irrigated trial at Garden City.

Table 4.19. Crude protein (CP), neutral-detergent fiber (NDF), acid-detergent fiber (ADF), lignin (L), total digestible nutrients (TDN), and relative feed quality (RFQ) by seeding rate within a species for the 2023 dryland trial in Garden City, KS.

Species	Seeding Rate	CP	NDF	ADF	Lignin	TDN	RFQ
	Seeds ha^{-1}	%					
Forage							
Sorghum	370,000	13.2	54.1	36.2	4.65 a[a]	58.0	105
	740,000	13.6	54.1	36.4	4.47 a	57.6	104
	1,110,000	12.1	55.4	36.5	4.30 ab	58.6	104
	1,480,000	11.3	56.3	37.1	4.11 ab	58.1	101
	1,850,000	12.4	54.1	35.3	3.83 b	59.2	107
	2,220,000	12.9	53.7	37.1	4.67 a	56.9	103
	Mean	12.6 AB[b]	54.6 B	36.4	4.34 AB	58.0 AB	104 A
Sorghum-Sudan	370,000	11.8	56.4	37.2	4.70	57.4	99.4
	740,000	11.6	57.6	37.3	4.22	58.4	99.1
	1,110,000	11.4	57.3	37.3	4.16	58.3	99.4
	1,480,000	11.1	57.9	37.2	3.93	58.5	98.8
	1,850,000	11.5	57.5	37.3	4.26	58.0	98.7
	2,220,000	11.7	57.0	37.0	3.88	58.7	101
	Mean	11.5 C	57.3 A	37.2	4.19 B	58.2 AB	99.3 B
Sudangrass	370,000	12.4	53.6	36.2	5.02 a	58.0	106

	740,000	11.9	56.3	36.7	4.36 ab	59.1	103
	1,110,000	11.5	57.4	36.7	4.13 b	59.0	100
	1,480,000	10.1	57.4	37.5	4.21 b	59.0	100
	1,850,000	12.6	55.1	35.8	3.97 b	58.9	104
	2,220,000	11.4	56.4	36.8	4.12 b	58.8	102
	Mean	11.6 BC	56.0 AB	36.6	4.30 AB	58.8 A	103 AB
Pearl Millet	370,000	15.1	50.7 b	36.2	5.75 a	55.7 c	108
	740,000	13.3	54.6 ab	37.2	5.06 a	56.4 bc	101
	1,110,000	12.6	55.5 ab	36.2	4.08 b	59.1 a	104
	1,480,000	13.6	55.5 ab	36.2	3.96 b	59.0 a	104
	1,850,000	11.8	57.4 a	37.2	3.99 b	58.6 a	100
	2,220,000	11.4	56.7 a	37.1	4.25 b	58.3 ab	101
	Mean	13.0 A	55.0 B	36.7	4.51 A	57.9 B	103 AB

[a]Seeding rate means followed by the same lower-case letter within a species are not significantly different ($\alpha = 0.05$). If there are not any lower-case letters present, means are not significantly different.
[b]Species means followed by the same upper-case letter within a column are not significantly different ($\alpha = 0.05$). If there are not any upper-case letters present, means are not significantly different.

Table 4.20. Nutritive value per area for a species within an environment and results of type III test of fixed effects in Garden City and Hays, KS 2022-23.

Environment	Species	CP Yield	TDN Yield
		kg ha^{-1}	
2022 Garden City Irrigated	Forage Sorghum	711.2 a[a]	3250 a
	Sorghum-Sudan	664.9 ab	3201 a
	Sudangrass	691.8 a	3049 a
	Pearl Millet	576.9 b	2620 b
	Mean	661.2 A[b]	3030 B
2023 Garden City Irrigated	Forage Sorghum	601.2 a	3416 a
	Sorghum-Sudan	600.2 a	3473 a
	Sudangrass	556.4 ab	3114 b
	Pearl Millet	505.1 b	2957 b
	Mean	565.8 B	3240 A
2023 Garden City Dryland	Forage Sorghum	581.8 b	2691 b
	Sorghum-Sudan	710.0 a	3572 a
	Sudangrass	673.5 a	3405 a
	Pearl Millet	638.0 ab	2872 b
	Mean	650.8 A	3135 AB
2023 Hays Dryland	Forage Sorghum	541.6 b	3582 a
	Sorghum-Sudan	764.0 a	4204 a
	Sudangrass	641.9 ab	3753 a

	Pearl Millet	597.6 b	2528 b	
	Mean	636.3	3517	

Fixed Effects	Garden City CP Yield	Garden City TDN Yield	Hays CP Yield	Hays TDN Yield
	P>F			
Seeding Rate (SR)	<0.0001	<0.0001	0.6176	0.0526
Species	<0.0001	<0.0001	0.0024	<0.0001
Environment	<0.0001	0.0027	—	—
Seeding Rate × Species	0.2112	0.2442	0.8104	0.7219
Seeding Rate × Environment	0.1983	0.6956	—	—
Species × Environment	0.0005	<0.0001	—	—
SR × Species × Environment	0.1381	0.4206	—	—

[a]Species means followed by the same lower-case letter within an environment are not significantly different (α =0.05).
[b]Environment means followed by the same upper-case letter within a column are not significantly different (α =0.05). The Hays environment was not compared to the Garden City environments due to heterogenous variance between the two sites.

Table 4.21. Pearson correlation coefficients among seeding rate (SR), plant population (Pop), forage mass (FM), plant height (height), tillers, leaf-to-stem ratio (LSR), stalk diameter (SD), crude protein (CP), neutral-detergent fiber (NDF), acid-detergent fiber (ADF), lignin, total digestible nutrients (TDN), and relative feed quality (RFQ) for forage sorghum across all trials in 2022-23 (n=96).[a]

	SR	Pop	FM	Height	Tillers	LSR	SD	CP	NDF	ADF	Lignin	TDN
Pop	**0.894**											
FM	**0.549**	**0.496**										
Height	-0.200	-0.092	0.161									
Tillers	**-0.292**	**-0.502**	0.134	**0.282**								
LSR	0.126	-0.083	0.014	**-0.554**	0.130							
SD	**-0.633**	**-0.561**	**-0.429**	**0.361**	**0.278**	**-0.422**						
CP	**-0.204**	-0.102	**-0.357**	0.048	-0.072	**-0.249**	**0.333**					
NDF	-0.053	0.039	0.119	**0.554**	0.065	**-0.463**	**0.215**	-0.041				
ADF	0.001	0.114	0.093	**0.484**	-0.013	**-0.541**	**0.268**	0.151	**0.915**			
Lignin	-0.062	0.0719	-0.112	**0.311**	-0.079	**-0.591**	**0.372**	**0.527**	**0.581**	**0.788**		
TDN	0.019	-0.101	0.090	**-0.316**	0.047	**0.549**	**-0.348**	**-0.487**	**-0.708**	**-0.898**	**-0.913**	
RFQ	0.032	-0.080	-0.034	**-0.491**	-0.014	**0.561**	**-0.301**	**-0.203**	**-0.939**	**-0.980**	**-0.786**	**0.904**

[a]Values in bold are statistically significant (α =0.05).

Table 4.22. Pearson correlation coefficients among seeding rate (SR), plant population (Pop), forage mass (FM), plant height (height), tillers, leaf-to-stem ratio (LSR), stalk diameter (SD), crude protein (CP), neutral-detergent fiber (NDF), acid-detergent fiber (ADF), lignin, total digestible nutrients (TDN), and relative feed quality (RFQ) for pearl millet across all trials in 2022-23 (n=96).[a]

	SR	Pop	FM	Height	Tillers	LSR	SD	CP	NDF	ADF	Lignin	TDN
Pop	**0.660**											
FM	**0.288**	**0.443**										
Height	-0.180	0.034	**0.427**									
Tillers	**-0.556**	**-0.777**	**-0.438**	-0.097								
LSR	-0.013	**-0.243**	**-0.207**	**-0.235**	0.189							
SD	**-0.343**	0.033	0.193	**0.428**	-0.017	-0.187						
CP	-0.046	**-0.356**	**-0.396**	**-0.562**	0.153	**0.304**	**-0.324**					
NDF	0.052	**0.437**	**0.428**	**0.510**	**-0.326**	**-0.523**	**0.332**	**-0.764**				
ADF	0.010	**0.382**	**0.369**	**0.476**	**-0.309**	**-0.572**	**0.314**	**-0.643**	**0.927**			
Lignin	**-0.260**	0.074	0.138	0.153	-0.151	**-0.533**	**0.327**	-0.118	**0.381**	**0.603**		
TDN	0.113	-0.173	-0.108	-0.135	**0.207**	**0.530**	-0.193	0.098	**-0.530**	**-0.768**	**-0.830**	
RFQ	0.006	**-0.415**	**-0.401**	**-0.472**	**0.332**	**0.586**	**-0.349**	**0.657**	**-0.962**	**-0.978**	**-0.573**	**0.726**

[a]Values in bold are statistically significant (α =0.05).

Table 4.23. Pearson correlation coefficients among seeding rate (SR), plant population (Pop), forage mass (FM), plant height (height), tillers, leaf-to-stem ratio (LSR), stalk diameter (SD), crude protein (CP), neutral-detergent fiber (NDF), acid-detergent fiber (ADF), lignin, total digestible nutrients (TDN), and relative feed quality (RFQ) for sudangrass across all trials in 2022-23 (n=96).[a]

	SR	Pop	FM	Height	Tillers	LSR	SD	CP	NDF	ADF	Lignin	TDN
Pop	**0.889**											
FM	**0.466**	**0.387**										
Height	**-0.256**	**-0.207**	-0.083									
Tillers	**-0.684**	**-0.695**	**-0.365**	**0.338**								
LSR	0.138	0.031	**0.205**	**-0.622**	-0.188							
SD	**-0.470**	**-0.425**	-0.180	**0.447**	**0.471**	**-0.456**						
CP	**-0.211**	-0.188	-0.125	**0.361**	**0.257**	-0.154	**0.301**					
NDF	0.147	**0.238**	0.093	**0.365**	-0.043	**-0.457**	0.125	**-0.254**				
ADF	0.070	0.200	-0.044	**0.439**	0.022	**-0.539**	**0.202**	-0.061	**0.902**			
Lignin	-0.074	0.098	-0.061	0.111	0.045	**-0.390**	0.160	0.042	**0.583**	**0.668**		
TDN	-0.008	-0.150	0.128	**-0.437**	-0.085	**0.564**	**-0.238**	**-0.269**	**-0.699**	**-0.907**	**-0.704**	
RFQ	-0.100	**-0.219**	0.001	**-0.421**	-0.018	**0.555**	-0.182	0.045	**-0.943**	**-0.975**	**-0.680**	**0.891**

[a]Values in bold are statistically significant ($\alpha = 0.05$).

Table 4.24. Pearson correlation coefficients among seeding rate (SR), plant population (Pop), forage mass (FM), plant height (height), tillers, leaf-to-stem ratio (LSR), stalk diameter (SD), crude protein (CP), neutral-detergent fiber (NDF), acid-detergent fiber (ADF), lignin, total digestible nutrients (TDN), and relative feed quality (RFQ) for sorghum-sudan across all trials in 2022-23 (n=96).[a]

	SR	Pop	FM	Height	Tillers	LSR	SD	CP	NDF	ADF	Lignin	TDN
Pop	**0.896**											
FM	**0.439**	**0.352**										
Height	**-0.327**	**-0.290**	**-0.244**									
Tillers	**-0.625**	**-0.669**	**-0.421**	**0.320**								
LSR	-0.003	-0.048	**0.259**	**-0.515**	-0.087							
SD	**-0.600**	**-0.578**	**-0.374**	**0.249**	**0.517**	**-0.395**						
CP	-0.116	-0.161	0.099	0.005	0.006	0.094	0.093					
NDF	0.012	0.060	-0.149	**0.436**	-0.094	**-0.444**	0.075	**-0.285**				
ADF	-0.019	0.068	**-0.256**	**0.490**	-0.087	**-0.482**	0.109	**-0.207**	**0.914**			
Lignin	-0.145	-0.055	**-0.221**	**0.339**	-0.080	**-0.365**	0.188	0.156	**0.653**	**0.774**		
TDN	0.010	-0.063	**0.235**	**-0.421**	0.102	**0.487**	-0.164	-0.088	**-0.760**	**-0.908**	**-0.882**	
RFQ	-0.010	-0.089	0.185	**-0.462**	0.104	**0.500**	-0.124	0.151	**-0.958**	**-0.967**	**-0.789**	**0.911**

[a]Values in bold are statistically significant (α =0.05).

Table 4.25. Partial economic returns ($ ha^{-1}) according to forage sorghum seeding rate in Garden City, KS and Hays, KS 2022-24, assuming seed costs of $3.30 per kg and a market price of $0.12 per kg of hay.

Seeding rate	Garden City Irrigated			Garden City Dryland		Hays Dryland	
(seeds ha^{-1})	2022	2023	2024	2023	2024	2023	2024
	$ ha^{-1}						
370,000	286.13	378.32	687.15	395.44	336.42	400.80	521.29
740,000	374.04	398.87	511.52	386.60	423.60	496.42	699.76
1,110,000	385.51	402.56	–––––	407.22	–––––	478.85	–––––
1,480,000	414.03	386.99	619.94	381.47	**590.08**	483.78	**815.49**
1,850,000	400.19	381.80	–––––	371.19	–––––	470.96	–––––
2,220,000	**468.64**[a]	**461.68**	**887.99**	**407.23**	514.46	**639.88**	679.25
2,960,000	–––––	–––––	782.68	–––––	512.61	–––––	750.09
3,700,000	–––––	–––––	629.35	–––––	395.37	–––––	618.25
4,440,000	–––––	–––––	874.16	–––––	374.31	–––––	736.01
LSD 0.05	99.19	75.02	473.5	87.25	147.72	250.68	185.73

[a]Highest return for each site-year is in bold.

Table 4.26. Change in partial economic returns in ($ ha^{-1}) when increasing forage sorghum seeding rate from 2.22 m seeds ha^{-1} to 4.44 m seeds ha^{-1} for a range of seed costs and hay market prices using 2024 irrigated trial data from Garden City, KS.

Seed Cost	Hay Market Price				
$ ha^{-1}	$ kg^{-1}				
	0.06	**0.09**	**0.12**	**0.15**	**0.18**
1.10	16.51	48.18	79.86	111.54	143.21
3.30	-77.17	-45.50	-13.83	17.85	49.53
5.50	-171.97	-140.29	-108.61	-76.93	-45.25

Table 4.27. Change in partial economic returns in ($ ha^{-1}) when increasing forage sorghum seeding rate from 1.48 m seeds ha^{-1} to 2.22 m seeds ha^{-1} for a range of seed costs and hay market prices using 2023-24 dryland trial data from Garden City and Hays, KS.

Seed Cost	Hay Market Price				
$ ha^{-1}	$ kg^{-1}				
	0.06	**0.09**	**0.12**	**0.15**	**0.18**
1.10	4.05	13.79	23.73	33.56	43.40
3.30	-27.17	-17.34	-7.50	2.34	12.17
5.50	-58.77	-48.90	-39.10	-29.27	-19.43

Table 4.28. Partial economic returns ($ ha⁻¹) for combined sorghum-sudan and sudangrass seeding rates in Garden City and Hays, KS 2022-23, assuming seed costs of $3.30 per kg and a market price of $0.12 per kg of hay

Seeding Rate	Garden City Irrigated		Garden City Dryland	Hays Dryland
(seeds ha^{-1})	2022	2023	2023	2023
	$ ha^{-1}			
370,000	299.87	329.02	455.12	582.13
740,000	392.09	366.86	516.33	**631.62**
1,110,000	351.33	399.18	531.46	495.54
1,480,000	**418.11**	390.64	543.79	590.95
1,850,000	387.62	394.83	**591.28**	596.30
2,220,000	395.49	**421.07**	556.24	548.73
LSD 0.05	61.71	64.97	54.67	119.21

[a]Highest return for each site-year is in bold.

Table 4.29. Change in partial economic returns ($ ha^{-1}) when increasing sorghum-sudan and sudangrass seeding rate from 1.48 M seeds ha^{-1} to 2.22 M seeds ha^{-1} for a range of seed costs and hay market prices using 2022-23 irrigated trial data from Garden City, KS.

Seed Cost	Hay Market Price				
$ ha^{-1}	$ kg^{-1}				
	0.06	0.09	0.12	0.15	0.18
1.10	-5.23	6.55	18.33	30.11	41.89
3.30	-19.67	-7.89	3.89	15.67	27.45
5.50	-48.53	-36.75	-24.97	-13.19	-1.41

Table 4.30. Change in partial economic returns ($ ha^{-1}) when increasing sorghum-sudan and sudangrass seeding rate from 0.74 M seeds ha^{-1} to 1.85M seeds ha-1 for a range of seed costs and hay market prices using 2023 dryland trial data from Garden City and Hays, KS.

Seed Cost	Hay Market Price				
$ ha^{-1}	$ kg^{-1}				
	0.06	0.09	0.12	0.15	0.18
1.10	20.71	41.88	63.05	84.22	105.39
3.30	-22.53	-1.36	19.81	40.98	62.15
5.50	-65.82	-44.65	-23.48	-2.31	18.86

Table 4.31. Partial economic returns ($ ha^{-1}) according to pearl millet seeding rate in Garden City, KS and Hays, KS 2022-23, assuming seed costs of $3.30 per kg and a market price of $0.12 per kg of hay.

Seeding Rate	Garden City Irrigated		Garden City Dryland	Hays Dryland
(seeds ha^{-1})	2022	2023	2023	2023
	$ ha^{-1}			
370,000	272.71	363.97	405.60	278.75
740,000	282.69	343.38	472.04	**559.43**
1,110,000	339.52	341.94	462.87	353.90
1,480,000	365.39	**431.30**	468.15	286.04
1,850,000	[a]**368.54**	348.46	**527.02**	442.88
2,220,000	327.41	370.18	492.80	388.19
LSD 0.05	73.39	69.83	102.75	262.76

[a]Highest return for each site-year is in bold.

Table 4.32. Change in partial economic returns ($ ha^{-1}) when increasing pearl millet seeding rate from 1.11 M seeds ha^{-1} to 1.85M seeds ha^{-1} for a range of seed costs and hay market prices using 2022-23 irrigated trial data from Garden City, KS.

Seed Cost	Hay Market Price				
$ ha^{-1}	$ kg^{-1}				
	0.06	0.09	0.12	0.15	0.18
1.10	12.15	21.48	30.81	40.14	49.47
3.30	-0.88	8.45	17.78	27.11	36.44
5.50	-13.91	-4.58	4.75	14.08	23.41

Table 4.33. Change in partial economic returns ($ ha^{-1}) when increasing pearl millet seeding rate from 0.74 M seeds ha^{-1} to 1.85M seeds ha-1 for a range of seed costs and hay market prices using 2023 dryland trial data from Garden City and Hays, KS.

Seed Cost	Hay Market Price				
$ ha^{-1}	$ kg^{-1}				
	0.06	0.09	0.12	0.15	0.18
1.10	-10.50	-10.87	-11.24	-11.61	-11.98
3.30	-30.05	-30.42	-30.79	-31.16	-31.53
5.50	-49.59	-49.96	-50.33	-50.70	-51.07