STRATEGIES TO EXTEND FORAGE PRODUCTION WINDOW IN BERMUDAGRASS PASTURES

By

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Abstract: In Oklahoma, bermudagrass-based cattle producers rely on summer bermudagrass [*Cynodon dactylon* (L.) Pers.] production excess to feed cattle from late fall to early spring. However, this excess forage may not be produced in dry years, and if good summer rainfall allows for forage surplus, harvesting hay is costly. Stockpiling bermudagrass is an alternative strategy to provide winter feed. Nevertheless, the low forage quality of stockpiled bermudagrass necessitates supplementation, meaning extra costs. On the other hand, winter wheat (*Triticum aestivum* L.) is a high-quality forage commonly cultivated in the area. Thus, interseeding winter wheat in dormant bermudagrass pastures may provide high-quality forage for the spring. Thus, our objective was to compare the total forage yield and quality of three different forage production systems: (i) in-season bermudagrass (BER), (ii) in-season + stockpiled bermudagrass (BER+STOCK), and (iii) interseeded winter wheat into bermudagrass (BER+WHEAT). Data were collected near Perkins, OK, in 2021 and 2022. The experiment was set in a randomized complete block design with four replications. The main plots were six bermudagrass varieties, and the subplots were the three different forage production systems. In-season bermudagrass forage was collected every six weeks (three harvests) during the summer, stockpiled bermudagrass forage was collected in the winter, and interseeded wheat forage was collected in late spring. Samples were dry, forage yield calculated, and nutritive value indicators analyzed. The BER+WHEAT system had the highest total forage production, followed by BER+STOCK and BER. In addition, almost half of the total forage produced in the BER+WHEAT was during late spring. The BER+WHEAT system increased total forage production while maintaining similar quality to in-season bermudagrass. Although the BER+STOCK system increased forage total season forage production compared to BER, its nutritive value was low, necessitating supplementation.

TABLE OF CONTENTS

Chapter Page

Chapter Page

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER I

REVIEW OF LITERATURE

Bermudagrass Origin and Distribution

Bermudagrass [*Cynodon dactilon* (L.) Pers.] is a perennial warm-season grass of the Poaceae family that originated in Africa. However, it has spread worldwide and can be found in tropical and temperate areas between 45' N and 45' S (Taliaferro, 1995). In the U.S., this grass is known as bermudagrass because the first plants were introduced from Bermuda Island (Burton, 1993).

According to Callahan & Engel (1965), bermudagrass was introduced to Savannah, Georgia, U.S., in the late 1700s by Governor Henry Ellis Burton. Henceforward, Howard (1881), stating that in the mid-1800s, bermudagrass was widely used in the southern U.S., becoming one of the most commonly grown forage species in the region. In Oklahoma, due to bermudagrass' tolerance to a wide range of environmental conditions such as temperature, precipitation, and soil, it is used across the state for pasture, hay, turf, soil stabilization, and remediation (Taliaferro, 1995).

Temperature is a crucial environmental constraint limiting bermudagrass applicability (Hu, 2020). Bermudagrass is not found in the northern regions of the United States due to being often limited by the lower temperatures and shorter growing seasons (Taliaferro, 2004). Some bermudagrass cultivars better suited for growth in cooler climates have been developed; however, bermudagrass production in the northern U.S. remains temperature-limited (Burton, 1993). Bermudagrass will continuously grow throughout the year in warm and tropical regions closer to the equator, while its growth will be reduced during long periods of cooler weather (Christians et al., 2011).

Bermudagrass Morphology

Bermudagrass is a sod-forming, warm-season grass that can be established from seed, sod, or sprigs (Christians et al., 2011). Its leaves are smooth and sparsely hairy on both surfaces, with 50-150 mm long and 2-5 mm wide leaf blades. Leaves emerge, alternating on opposite sides of the stem, and their margins are slightly rough. Leaves are absent in the auricle, and its ligule is a fringe of hairs of approximately 0.5 mm (Double, 1996).

The bermudagrass stolons have lateral buds developing from the nodes, producing stems that can laterally grow up to 40 cm (in some rare cases, up to 90 cm) in height (Double, 1996). The inflorescence comprises 3-7 fingerlike spikes measuring 3-10 cm in width that contain oval, red-colored, and 1.5 mm long seeds (Double, 1996).

The fibrous root system of bermudagrass is continuously being renewed. Degradation of the mature roots occurs throughout the growing season, and new ones are constantly produced. The mature roots have yellow to brown coloration, while the new roots are white. Robust rhizomes compose the bermudagrass deep and vigorous root system (up to 0.9 m), and its development occurs primarily within 0-25 cm depth (Beard, 1973). Additionally, bermudagrass can rapidly produce new shoots from its underground stems, allowing it to quickly recover from damage and maintain its dense growth habit (Double, 1996).

Bermudagrass Physiology

Temperature is a crucial controlling factor in warm-season grass growth and dormancy. According to McCurdy et al. (2020), the basal temperature of the bermudagrass is estimated at 13.1°C , and the optimal temperature for bermudagrass leaves and stems growth is 32.7°C. Another variable affected by the change in temperature is root production. McCurdy et al. (2020) found that dry root mass decreased linearly with an increase in temperature, ranging from 1.7 to 4.2 g/m^2/°C depending on the cultivar, with daily temperature ranging from 20°C to 40°C .

According to Christians et al. (2011), bermudagrass begins dormancy when the air temperature is below 10°C during fall or early winter. At this point, leaves and stems stunt growth, and carbohydrate reserves translocate to the rhizomes, stolons, and roots. Bermudagrass ultimately enters dormancy and turns brown when the air temperature decreases to 0°C (Mirabile et al., 2016). While the leaves and stems stop growth at the onset of freezing temperatures, roots and rhizomes will continue to develop for several weeks. Bermudagrass' roots, rhizomes, and some stolons stay dormant until mid to late spring, then will resume physiological activity when soil temperature persists for about 3-5 days consecutively above 10 °C (Double, 2001). This stage of a plant beginning a new growth cycle is called green-up. Depending on environment, bermudagrass can experience winter dormancy for up to 6 months (Zhang et al., 2021).

Bermudagrass, as a warm-season grass, is classified as a C4 plant, and its photosynthetic processes differ from those of cool-season grasses (C3 plants). The C4 plants have a specialized mechanism for photosynthesis that allows them to efficiently capture carbon dioxide (CO_2) in high-light and high-temperature conditions. In the C4 pathway, CO_2 is initially fixed into a four-carbon compound in mesophyll cells and then transported to bundle sheath cells, where it is converted into glucose through the Calvin cycle (Moser et al., 2004). This two-step process allows C4 plants to concentrate CO_2 near the site of carbon fixation and reduces photorespiration, leading to increased water and energy efficiency (Ghannoum, 2009). As a result, warm-season grasses often utilize water more effectively than cool-season grasses (Moser et al., 2004).

Bermudagrass is tolerant to extremes in soil moisture, meaning it survives in dry and waterlogged environments. (Gamble and Rhoades, 1964; Burton et al., 1954; Burton et al., 1957). Beard (1973) claims that bermudagrass reaches its growth threshold when soil moisture levels decline to around 40-50% of the plant's maximum accessible water. When the soil moisture level drops below a certain threshold, bermudagrass may undergo drought stress and enter a state of dormancy as a survival mechanism. While the majority of Bermuda grass's roots typically remain within a depth of 15 cm, it is possible for them to extend to depths of 1.82 or more (Duble, n.d.) Bermudagrass drought tolerance is attributed to its physiological and rooting characteristics, such as a deep and dense root system enabling the plant to access water and nutrients from deeper soil layers, closing stomata, and reduced water loss through transpiration. Due to those features, bermudagrass retains its color and density during the early phases of drought and survives longer without additional irrigation (Christians et al., 2011).

Bermudagrass Fertility Management

To ensure high yields and good forage quality, proper fertilization is essential. The first factor to consider before fertilizing bermudagrass is soil pH. According to McCarty and Miller (2002), Bermudagrass performs its best at a soil pH ranging from 5.5 to 6.5. Soil pH under 5.0 is highly acidic for bermudagrass, which can produce toxic elements in the plants and reduce the availability of certain nutrients, such as phosphorus and calcium. Alkaline soil pH (> 7.0) also limits the availability of many minor elements (McCarty and Miller, 2002).

In addition to soil pH, nitrogen (N) availability is critical in bermudagrass production. Nitrogen is the most crucial nutrient for producing high yields and good forage nutritive value in bermudagrass, which is indicated by crude protein (CP) and neutral detergent fiber (NDF) (Ball et al., 2007). Bermudagrass's growth benefits significantly from N fertilization, producing abundant forage when soil moisture is sufficient. Production is influenced by available nitrogen and moisture, as they are interlinked in the soil. The nitrogen recommendation for bermudagrass ranges from 56 to 168 kg of N ha^{-1}, which potentially produces 2 to 9 Mg ha^{-1} of forage. However, with advanced hay-type varieties, production can surge to 8-10 Mg $ha^{-1}$of forage (Redfearn et al., 2016).

Due to their relevance in plant physiological processes, phosphorus (P) and potassium (K) are given special consideration among the required nutrients for optimal plant development. Phosphorus is an essential nutrient for the growth and development of bermudagrass, and it plays a critical role in energy transfer, photosynthesis, and root development. Potassium also participates in critical plant activities, such as photosynthesis, water control, enzyme activation, and protein synthesis (Marschner, 2012). Phosphorus deficiency can result in reduced growth, thin leaves, and poor root development, while potassium deficiency can result in poor vegetation, reduced drought tolerance, and increased susceptibility to pests and diseases (Lesley, 1994).

Both macronutrients, phosphorus (P) and potassium (K), have recommendations based on soil test results. In forage systems, soil-test P and K values may decline over time due to the significant removal of aboveground biomass, potentially leading to deficiencies if nutrient removal is not countered with sufficient fertilizer rates (Barnes et al., 2007).

Bermudagrass Nutritional Value

Bermudagrass typically has a CP content ranging from 7% to 16%, depending on factors such as soil fertility, harvest time, and cultivar (Ball et al., 2007). The CP content of bermudagrass may decline as the growing season progresses, particularly in the reproductive stage (from anthesis to seed formation)(Barnes et al., 1999). According to Burton et al. (1963), as the cutting interval increased from 3 to 24 weeks, the crude protein content decreased from a concentration of 18.5% to 8.4% in the plant biomass.

In addition to CP, total digestible nutrients (TDN) typically range from 45% to 65%. The nutritional value and digestibility of bermudagrass are further understood through indicators like acid detergent fiber (ADF) and neutral detergent fiber (NDF) (Ball et al., 2002). Acid detergent fiber, representing the undigestible cellulose and lignin content portions, usually lies between 25% and 35%. On the other hand, according to Ball et al. (2002), NDF, a broader measure encompassing ADF components, digestible cellulose, and hemicellulose, tends to vary from 55% to 70% (Ball et al., 2002). As bermudagrass matures, ADF and NDF values increase, correlating with a decline in digestibility and animal intake (Rohweder et al., 1978).

In mature stands (i.e., after anthesis) or after a killing frost, bermudagrass nutritive value is reduced, limiting animal intake and growth (Burton, 1963). Thus, additional supplementation or alternative forage options might be necessary to compensate for bermudagrass low energy content and digestibility (Rankins and Pugh, 2012). Furthermore, low-forage quality bermudagrass affects not only animal performance but also animal health. According to Owens et al. (1998), forage species with low forage quality increase the risk of animal digestive disorders such as acidosis and bloat.

Drought Impact on Bermudagrass

Although bermudagrass is a drought-tolerant forage grass adapted to a variety of soils and warm climates (McCarty and Miller, 2002; Kim et al., 2009; Zhao et al., 2011), it requires adequate soil moisture for growth (Taliaferro, 2003). In regions where the average annual precipitation exceeds 711 mm in Oklahoma, such as the central and eastern of the state, bermudagrass demonstrates the best adaptation (Redfearn et al., 2016).

The drought impact on bermudagrass is influenced by soil type, variety, and management practices (Christians et al., 2011). Soils exhibit diverse characteristics regarding their water retention capabilities, drainage rates, and aeration qualities. For example, sandy soils, characterized by their bigger particle sizes and increased porosity, tend to facilitate quick water drainage, providing adequate aeration for root growth. However, low water retention in sandy soil makes bermudagrass more vulnerable to drought-induced stress. On the other hand, clayey soils, consisting of finer particles, have a higher water retention capacity due to their reduced particle size. While this phenomenon may provide advantages in terms of drought tolerance, the decreased rate of drainage might sometimes result in less oxygen accessibility for the roots, hence possibly inducing stress on the grass.

Grazing bermudagrass varieties generally exhibit reduced water demands and greater tolerance to drought conditions than most hay varieties due to their increased amount of rhizomes and stolon, which typically experience a decrease in density during prolonged periods of drought (Christians et al., 2011). Thus, selecting varieties that are adequate to reduced moisture levels and have lower irrigation and water demands has become a crucial concern (Kim and Beard, 1988).

Management approaches significantly impact the drought resistance of bermudagrass. According to Trenholm et al. (2001), excessive fertilization, specifically with nitrogen, has been found to amplify water requirements and vulnerability to drought potentially. Conversely, maintaining appropriate soil fertility can foster the development of a more robust and resilient root system, thereby enhancing drought resistance.

Bermudagrass and Wheat Water Use Efficiency

The concept of plant water use efficiency (WUE) is the ratio of atmospheric carbon fixation, either as forage, fiber, or grain, relative to the volume of water evapotranspiration by a given crop (Stanhill, 1986). This ration quantifies water resource productivity in generating forage, fiber, or grain yields of specific crop systems (Leakey et al., 2019). Increasing plant water use efficiency is often considered crucial for sustainable agriculture

(Leakey et al., 2019) and water conservation since agriculture contributes to approximately 70% of freshwater consumption worldwide, according to Connor (2015).

As drought conditions intensify and the global population grows, a continued rise in water use efficiency is essential for ensuring food security and sustainability (Bu et al., 2013). Throughout history, numerous instances of rural exodus have been driven by drought conditions. Prolonged drought periods can cause agricultural productivity to decline, resulting in food insecurity and economic hardship for rural communities. In response to these challenges, many communities have been compelled to migrate from rural areas to urban centers or other regions for better opportunities and resources (Pereira et al., 2007). Advances in agronomic and physiological knowledge, coupled with molecular genetic approaches, have the potential to improve crop water productivity substantially; however, to achieve sustainable results, a multidisciplinary team approach is necessary (Morison, 2008).

Several factors influence water use efficiency in agriculture, including crop type, irrigation method, soil properties, and climatic conditions. Different crops have varying water requirements, and their water use efficiency can be impacted by factors such as plant genetics and management practices (Condon et al., 2004). According to Ullah et al. (2019), irrigation methods, such as drip irrigation or sprinkler systems, can significantly affect water use efficiency by delivering water more precisely and reducing losses due to evaporation and runoff. Soil properties, including texture, structure, and organic matter content, can influence the water-holding capacity and infiltration rates, affecting water availability for plant uptake (Brady and Weil, 1996). Climatic conditions, such as temperature, humidity, and rainfall, can also impact water use efficiency by altering evapotranspiration rates and the overall water demand of crops (Hatfield and Dold, 2019).

The water use efficiency of different small grains might vary significantly depending on the species and kind of harvest (forage or grain). The WUE of small grains increases when the crop is harvested as a feed compared to grain, primarily due to the larger biomass obtained from the harvest. Additionally, forage production often demands less irrigation compared to grain production. According to Sadras et al. (2006), the water use efficiency of wheat cultivated for grain production ranges from 0.50 to 0.56 Mg ha^{-1} mm^{-1}. In contrast, Marsalis (2018) reported a WUE of 0.79 Mg ha^{-1} mm^{-1} for small grain fodder.

Strategies to Extend Bermudagrass Pastures Grazing Window in the Central Great Plains

Bermudagrass ceases growth, entering dormancy when temperatures reach 0 °C. This period in Central Great Plains (CGP) starts typically from October, lasting approximately five months until March. During this time, producers rely on hay and cool-season pastures to meet cattle's nutritional requirements. Often, producers invest in summer hay production; otherwise, they must purchase hay and feed to ensure enough cattle feedstock to endure the winter. Nonetheless, buying harvested forage increases production costs, culminating in lower profits. An alternative to alleviate hay and feed costs is to plant annual cool-season small grains, such as winter wheat, in other farmlands to provide forage for the fall and spring. However, this extra farmland could be allocated to grain production if the existing bermudagrass pasture's forage production window is extended from mid-fall to late spring next year.

Extending grazing in existing pastures can reduce the amount of harvested forage needed to maintain cow performance, lower production costs associated with winter feeding, and promote farm sustainability (Hitz and Rusell, 1998). According to Edwards & Warren (2017), a sod-seeded small grain crop that has been appropriately fertilized has the potential to provide between 1.7 and 3.4 Mg ha^{-1} of fall forage and 4.5 to 6.7 Mg ha^{-1} of full-season forage.

Several winter forage production strategies have been proposed to provide adequate forage during winter, including stockpiling bermudagrass (Matches and Burns, 1985) and interseeding annual cool seasons into bermudagrass pastures. Each of these strategies has its advantages and challenges, and the choice of strategy may depend on factors such as available resources, climate, and management goals.

Stockpiling Bermudagrass

Stockpiling bermudagrass, aka standing hay, consists of accumulating forage growth during the late summer and fall months without harvesting (Mays and Washko, 1960). Then, after killing frost, the pasture provides winter forage for livestock. Nitrogen fertilization is crucial for promoting forage growth and nutritive value during fall/winter. Forages are often stockpiled for utilization in the autumn and winter seasons. However, they may be accumulated for utilization during any anticipated insufficiency (Lalman et al., 2000).

Nitrogen fertilizer in late summer enhances stockpiled bermudagrass forage protein concentration (Webster et al., 1965). However, the digestibility of this late-summer fertilized bermudagrass forage tends to decrease during the winter months (Taliaferro et al., 1987). According to Taliaferro et al. (1987), stockpiled bermudagrass cultivar Midland showed a decrease of approximately 150 g kg^{-1} in In Vitro Dry Matter Digestibility (IVTDMD) from November to February in Perkins, OK.

Depending on the available nitrogen in the soil and the expected yield, farmers typically apply 55 to 115 kg ha^{-1} in late August (Lalman et al., 2017). According to Lalman et al. (2017), it was found that this range of nitrogen fertilizer recommendation produced from 680 to 1134 kg of forage, varying depending on application time, precipitation time, and precipitation amount. According to Guretzky (2008), on average, the dry matter consisted of 56% Total Digestible Nutrients (TDN) and crude protein (CP) concentrations of 6.0%, 6.9%, 7.9%, and 8.7% when nitrogen was applied at 0, 56, 112, and 168 kg ha^{-1}, respectively.

An economic evaluation demonstrated that the use of stockpiled bermudagrass as feed may result in cost savings ranging from 33% to 60% compared to the production and utilization of bermudagrass hay sourced from the same agricultural establishment (Lalman et al., 2000).

Interseeding Winter Wheat into Bermudagrass Pastures

Interseeding winter wheat into bermudagrass produces high-quality forage during bermudagrass dormancy. This strategy aims to improve forage yield and quality, provide a more diverse and nutritious forage base, and extend the grazing season for livestock (Ball et al., 2007). In addition, the fall-established wheat grown in the bermudagrass pasture can be used to extend the grazing period.

According to Edwards & Warren (2017), to establish winter wheat successfully and allow for early grazing, it should be seeded in the fall season. However, this seeding should occur late enough to prevent competition between the wheat seedlings and bermudagrass for moisture and nutrients. An optimal time for wheat seeding in central Oklahoma is mid-September, as the shorter day length and cooler nights typically slow down bermudagrass growth, and the likelihood of fall showers increases the chance of cereal seedling establishment. Prior to seeding, the bermudagrass cover should be reduced to no more than 1.5 mm in height to minimize shading and competition that can affect winter wheat germination. According to Edwards & Warren (2017), the recommended seeding rate for wheat interseeding is 135 to 170 kg ha^{-1}.

Some of the benefits of interseeding winter wheat into bermudagrass pasture are reduced cash outlay for winter supplementation of livestock, more efficient use of available land, additional profits from wheat production possible, more efficient use of seasonal precipitation and less erosion than conventionally seeded wheat pasture (Edwards & Warren, 2017).

CHAPTER II

STRATEGIES TO EXTEND FORAGE PRODUCTION WINDOW IN BERMUDAGRASS PASTURES

Abstract

In Oklahoma, bermudagrass-based cattle producers rely on summer bermudagrass [*Cynodon dactylon* (L.) Pers.] production excess to feed cattle from late fall to early spring. However, this excess forage may not be produced in dry years, and if good summer rainfall allows for forage surplus, harvesting hay is costly. Stockpiling bermudagrass is an alternative strategy to provide winter feed. Nevertheless, the low forage quality of stockpiled bermudagrass necessitates supplementation, meaning extra costs. On the other hand, winter wheat (*Triticum aestivum* L.) is a high-quality forage commonly cultivated in the area. Thus, interseeding winter wheat in dormant bermudagrass pastures may provide high-quality forage for the spring. Thus, our objective was to compare the total forage yield and quality of three different forage production systems: (i) in-season bermudagrass (BER), (ii) in-season + stockpiled bermudagrass (BER+STOCK), and (iii) interseeded winter wheat into bermudagrass (BER+WHEAT). Data were collected near Perkins, OK, in 2021 and 2022. The experiment was set in a randomized complete block design with four replications. The main plots were six bermudagrass varieties, and the subplots were the three different forage production systems. In-season bermudagrass forage was collected every six weeks (three harvests) during the summer, stockpiled bermudagrass forage was collected in the winter, and interseeded wheat forage was collected in late spring. Samples were dry, forage yield calculated, and nutritive value indicators analyzed. The BER+WHEAT system had the highest total forage production, followed by BER+STOCK and BER. In addition, almost half of the total forage produced in the BER+WHEAT was during late spring. The BER+WHEAT system increased total forage production while maintaining similar quality to in-season bermudagrass. Although the BER+STOCK system increased forage total season forage production compared to BER, its nutritive value was low, necessitating supplementation.

Introduction

Agriculture is an important sector in Oklahoma's economy. In 2021, Oklahoma's agricultural production sector generated approximately $7.7 billion in cash revenues and, combined with the state's agricultural product processing, accounted for 3.2% of the gross domestic product (Oklahoma Department of Agriculture, Food and Forestry, 2021). Beef cattle production is a significant portion of the Oklahoma agriculture sector, comprising 5.20×10^6 head in 2022, when Oklahoma ranked as the fourth largest beef cattle producer in the U.S. (USDA-NASS, 2022). Hence, a steady, appropriate amount of quality forage year-round for cattle consumption is key to maximizing beef cattle production systems' profit and sustainability. Nevertheless, summer drought due to high temperatures and erratic rainfalls reduces summer forage production and freezing temperatures prohibit forage growth during the summer on perennial pastures in the southern Great Plains, where most of the Oklahoma beef cattle production is concentrated (Baath et al., 2018).

Bermudagrass [*Cynodon dactylon* (L.) Pers.], being a warm-season, C4, perennial grass, that actively grows from late May to late September, maintaining decent amounts of forage production under high summer temperatures and water limited conditions experienced in the southern Great Plains (Ball et al., 2015). Thus, it is the most adopted tame forage species in Oklahoma pastures because it can lead to a production excess during the summer, which is traditionally hayed to feed cattle during winter. However, relying solely on bermudagrass pastures poses considerable challenges to cattle producers, especially during drought conditions (Ball et al., 2015). Moreover, even when enough rainfall allows for forage surplus, harvesting hay is costly, often resulting in significant financial strain on beef cattle producers (Redmon, 2002). Consequently, alternative economically viable forage production strategies must be developed to provide high-quality forage year-round (Franzluebbers, 2007).

In this context, winter wheat (*Triticum aestivum* L.) might be a compelling alternative to meet the winter forage demand previously sufficed by the bermudagrass hay surplus. In Oklahoma, winter wheat can serve as a dual-purpose crop when planted solely, meeting grain yield demands while offering high forage quality for livestock (Tabak et al., 2017). According to Ball et al. (2005), winter wheat forage's crude protein (CP) content varies with its growth stage, typically ranging from 15-20% during the boot stage, 12-16% at the flowering stage, and dropping to 8-12% when mature. The concentration of total digestible nutrients (TDN) for forage wheat was reported by Lalman and Highfill (2017) as 88%, by Hoppe and Tobin (2023) as 90%, and by Lollato et al. (2017) as superior to 80%. Also, according to Silva et al. (2021, 2022, 2023), the total forage production for the winter wheat variety OK Corral at Stillwater, Oklahoma, during the 2020-2021 and 2021-2022 production year was, respectively, 3.09 and 3.44 Mg ha^{-1}.

Perhaps interseeding winter wheat into dormant bermudagrass may provide a practical solution for extending the forage production window in bermudagrass pastures. This practice may reduce beef cattle producer's reliance on costly supplemental feeds while adding value and flexibility to existing pasture systems (Min et al., 2005).

Indeed, while incorporating winter wheat into existing pastures shows promise, it is not without challenges and uncertainties. Interseeding can lead to interspecies competition, potentially impacting the yield and quality of both winter wheat and bermudagrass. Introducing a new crop species may instigate changes in soil nutrient composition and alter microbial activity (Karlen et al., 1994). Moreover, from an economic perspective, farmers must weigh the benefits against potential costs related to interseeding implementation.

Stockpiling bermudagrass to extend winter grazing is another strategy that livestock producers adopt in Oklahoma. Stockpiling refers to allowing pasture grass to grow and accumulate during late fall and the beginning of winter, ensuring that grazing animals have a ready feed source during the otherwise barren winter months. With the ever-rising costs of hay and other supplemental feeds, stockpiling bermudagrass presents a cost-effective alternative (Adams et al., 1994; D'Souza et al., 1990; Hitz and Russell, 1998). Lalman et al. (2017) stated that, when managed correctly, stockpiled bermudagrass can save producers anywhere from \$0.25 to \$0.75 per day per cow compared to feeding hay. Over the winter season, these savings accumulate, presenting significant economic relief to farmers. However, the quality of bermudagrass diminishes during winter (Ball et al., 2015), necessitating supplementation to meet the cattle's nutritional needs, thereby incurring additional costs.

From an ecological and economic perspective, stockpiling bermudagrass reduces the need for mechanical harvesting, lowering fuel consumption, equipment depreciation, and greenhouse gas emissions. Given cattle producers' economic and environmental challenges during winter, there is still a limited understanding of alternative forage systems and a growing interest in investigating it. (Martin et al., 2017).

With these considerations, this study was designed to compare the biomass and quality of three forage production systems [interseeding winter wheat into bermudagrass, stockpiling bermudagrass, and in-season bermudagrass (conventional practice)] applied to six different bermudagrass cultivars (Greenfield, Goodwell, Midland, Midland99, Ozark and Tifton 44) in Perkins, OK. The selection of bermudagrass and winter wheat varieties was determined based on their frequent adoption in Oklahoma.

This study investigates the effects of winter strategies in bermudagrass summer production and total forage production. This project was carried out under the hypothesis that interseeding winter wheat into bermudagrass would be a recommended system option to increase grazing window in bermudagrass pastures, with increased total forage production while achieving higher quality, compared with the other two systems.

Material and Methods

Site Description

This study was conducted at the Cimarron Valley Research Station in Perkins, OK (35°59'9' "1" N 97°'2' "1" W). The research was developed in existing bermudagrass plots established in April 2017 and conducted as a variety performance trial until October 2020. The existing 24 bermudagrass plots (5.1 x 5.1 m) were arranged in randomized complete block design with four replications and consisting of six different bermudagrass cultivars, i.e., Goodwell, Greenfield, Midland, Midland99, Ozark, and Tifton44. The previous agricultural management used in the study area was described by Rocateli et al. (2019) and Rocateli and Abreu (2020). Soil type was mapped as fine-loamy, mixed, active, thermic Udic Argiustolls (Teller loam, 0 to 1% slopes soil series) (NRCS, 2008).

Experimental Design and Cultural Practices

Composite soil samples were collected to a depth of 0.15 m at the beginning of the experiment (early August 2021). Soil nutrient analysis was performed at Oklahoma State University's Soil, Water, and Forage Analytical Laboratory (SWFAL) (Zhang & Henderson, 2016). The pH analysis was performed using 1:1 soil to deionized water ratio. For NO3-N, 1 M KCl extraction was used and analyzed using cadmium reduction chemistry on a flow injection analyzer. For phosphorus (P) and potassium (K), Mehlich 3 extractions were analyzed using inductively coupled plasma (ICP). Soil analysis results are described in Table 2.

Soil analysis results indicated an average pH of 6.3, 12.8 mg kg^{-1} of NO_3-N, 17 mg kg^{-1} of P index, and 110 mg kg^{-1} of K index. After soil sampling, the existing bermudagrass plots (main plots) were split into three subplots (1.7 x 5.1 m) to accommodate three different forage systems management, i.e., in-season bermudagrass (BER), in-season + stockpiled bermudagrass (BER+STOCK), and in-season bermudagrass interseeded with winter wheat (BER+WHEAT). Thus, the experiment involved 6 cultivars × 3 forage systems × 4 blocks factorial arranged in a split-plot design with forage system composing the split.

The BER system represents the standard bermudagrass management in Oklahoma, which is bermudagrass forage produced and harvested every six weeks (at initial anthesis) from late spring (June) to early Fall (September) (Redfern & Rice, 2017). The subplots corresponding to BER were mowed with a rotary mower at 7.6 cm on September 23, 2021, and September 14, 2022, and kept fallow until late Spring bermudagrass green up. On April 29, 2022, 73.1 kg of P_20_5 ha^{-1} and 18.7 kg of K_2O_5 ha^{-1} were manually broadcasted in each BER subplot according to Oklahoma Cooperative Extension Service (OCES) recommendations (Arnall et al., 2018). A total of 168 kg of N ha^{-1} as urea was split into three 56 kg of N ha^{-1} applications. The first application was at full bermudagrass green up (May 5, 2022, and May 3, 2023), then N was applied right after the first and second bermudagrass cut. In both years, a total of three bermudagrass manual herbage samplings followed by total subplot harvest (defoliation) at a 7.6 cm stubble height using a mower (12-Bushel 3-BaMCSCS Mower, John Deere, Illinois, USA) were performed in BER subplots. The sampling and harvest dates were June 16, August 17, September 14 in 2022, June 14, August 2, and October 6 in 2023.

The BER+STOCK system followed the same cultural practices as BER until the second bermudagrass cut in both years, i.e., August 17, 2022, and August 2, 2023. However, after the second harvest, those subplots received an application of 56.1 kg of actual N ha^{-1} using urea as a nitrogen source on August 20, 2021, in the first year. In the second year, the same application was made on August 17, 2022, right after the last cut, before initiating the stockpiling process. In both years, the stockpile bermudagrass subplots were mowed at 3.8 cm with a rotary mower before N application. The cutting date for the first year was December 15, 2021, and December 15, 2022, for the second year.

The BER+WHEAT system followed the same cultural practices as BER in both years. However, subplots were sod seeded with winter wheat in early fall instead of kept fallow until late spring. Before winter wheat sod-seeding, the bermudagrass sod at BER+WHEAT subplots were scalped, i.e., mowed at 3.8 cm using a rotary mower. Hard red winter wheat 'OK Corral' (Oklahoma genetics INC, Stillwater, OK) was sod-seeded using a no-till drill (Kincaid Great Plains 600 Series Plot Seed Drill) at a seeding rate of 168.2 kg of pure life seed ha^{-1}, 19.1 cm row spacing, and 3.8 cm seed depth according to OCES recommendations (Edwards & Warren, 2017). During winter wheat sod seeding, 37.4 L ha^{-1} of ammonium polyphosphate (Plant Food Company INC, Cranbury, NJ) was in-furrow applied to promote seedling development. On October 14, 2021, and November 28, 2022, BER+WHEAT subplots were manually broadcasted with 67.3 kg of actual N ha^{-1}, 97.5 kg of P_20_5 ha^{-1}, and 18.7 kg of K_2O_5 ha^{-1} according to OCES recommendations (Edwards & Warren, 2017). Then, a second 63.7 kg of actual N ha^{-1} was manually broadcasted on March 15, 2022, and February 10, 2023.

Winter wheat herbage manual samplings followed by total subplot harvest (defoliation) using a mower (12-Bushel 3-BaMCSCS Mower, John Deere, Illinois, USA) were performed two times at each growing season. During early winter, wheat herbage was first sampled and harvested at a stubble height of 7.2 cm when the average canopy height was at least 0.20 m, and the crown roots, aka secondary roots, were visually observed by digging wheat plants from the ground. Then, wheat herbage was sampled and harvested at 3.2 cm stubble height when plants achieved the boot stage during late spring. Excessive drought during the fall of 2021 limited wheat herbage production; therefore, the sampling and harvest were performed on April 29, 2022. In the second wheat growing season, 2022-2023, the two samplings and harvests were performed, i.e., December 15, 2022, and April 14, 2023.

Finally, weeds were controlled on May 16, 2022, using 1.75 kg ha $^{-1}$ of PastureGard® HL Herbicide (CortevaTM Agriscience, Wilmington, DE) and 2.45 kg ha $^{-1}$ of GrazonNext® HL Herbicide (CortevaTM Agriscience, Wilmington, DE). In the second year, on March 24, 2022, weeds were controlled using 1.17 kg ha $^{-1}$ glyphosate (Roundup PowerMAX®, Monsanto, St. Louis, MO) just on BER and BER+STOCK subplots.

Data Collection

Weather Data

Daily and long-term average temperatures and precipitation were acquired from Perkins station at Oklahoma Mesonet website (www.mesonet.org) (McPherson et al., 2007). The field was within one kilometer of the Mesonet station.

Aboveground Biomass and Nutritive Values Indicators

At each harvest date, in-season and stockpiled bermudagrass herbage were sampled using a 0.5 m^2 quadrat randomly assigned in three representative areas of all subplots. All bermudagrass herbage within the quadrat was hand-clipped at its assigned stubble height using handheld electric shears (Gardena 8885-U 3-inch Cordless Lithium-Ion Grass Shears, Gardena, Ulm, Germany). Winter wheat herbage sampling consisted of hand clipping wheat herbage within three randomly assigned 1-m in a row using a 1-m stick as reference.

At every sampling day, the bermudagrass and wheat herbage samples from all evaluated systems were placed to dry in a forced-air oven at 55°C until a consistent weight was achieved (at least for seven consecutive days). The biomass samples were weighed and ground to pass a 1-mm sieve using a Wiley (Model 4 Wiley Mill, Thomas Scientific, Swedesboro, NJ) and Cyclotec mill (CT 293 Cyclotec, FOSS North America, Eden Prairie, MN). Then, the ground samples were analyzed using the Oklahoma State University

Forage Laboratory using near-infrared reflectance spectroscopy (NIRS DS3 F, FOSS North America, Eden Prairie, MN). The NIRS spectrum data were analyzed using the NIRS Forage and Feed Testing Consortium (Berea, KY) calibration for grass hay. The NIRS Forage and Feed Testing Consortium (Berea, KY) calibration calculated forage nutritive values for crude protein content (CP), neutral detergent fibers (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), and in vitro dry matter digestibility 48 hours (IVDTMD48).

The biomass sum of all harvests across all forage types in BER+WHEAT (i.e., in-season bermudagrass + winter wheat biomass), BER+STOCK (i.e., in-season bermudagrass + stockpiled bermudagrass) was named as total season biomass. The sum of all in-season bermudagrass harvests was named the total in-season bermudagrass biomass for all forage systems. Finally, punctual in-season bermudagrass biomass harvests were named first, second, or third bermudagrass harvests. Once stockpiled bermudagrass and winter wheat forage types had only one harvest each, their punctual biomass harvests were simply named stockpiled bermudagrass and winter wheat biomass, respectively.

Statistical Analysis

Three different linear mixed models accounting for the 6×3×4 factorial split-plot design nature were created using JMP pro 16 software SAS institute) to analyze the different facets of biomass production. The first model was used to analyze total season biomass. This model consisted of random effects for blocks and main plots and fixed effects for cultivar, forage system, and cultivar × forage system interaction. A second model was created to analyze the effect of winter wheat and stockpiled bermudagrass biomass production on subsequent in-season bermudagrass biomass. This model considered blocks and main plots as random effects and fixed effects for cultivar, forage system, and cultivar × forage system interaction. Also, only data from bermudagrass as forage type were used for this analysis. Finally, a third model to analyze the changes in biomass production throughout the season at different forage systems was created, consisting of random effects for block, main plot, and subplot, and fixed effects for cultivar, forage system, cultivar × forage system interaction, and harvest event (i.e., all harvest dates) nested within forage system.

Crude protein, NDF, ADF, lignin, and IVTDMD48 were analyzed following the same structure of the third biomass linear mixed model to evaluate changes in these nutritive value indicators throughout the season at different forage systems. Treatment means were separated by the LSMEANS procedure adjusted for the Tukey HSD test (JMP Pro 16; SAS Institute) when protected by F-tests significant at an α level of .05. It was found using residual analysis that the model assumptions were reasonably met for all models. Finally, the graphic depicting biomass production throughout the season at different forage systems was developed using R 4.3.0 (www.r-project.org).

Results

Precipitation Patterns

Figure 1A illustrates the distribution of total rainfall for winter wheat and stockpiled bermudagrass growing season: Oct 1, 2021 – Apr 30, from 1994 to 2022. The total rainfall amount during the 2021-2022 wheat growing season and stockpiled period was 272 mm. This total precipitation amount was the fourth-lowest total precipitation (i.e., within the first quartile and minimum value); thus, the 2021-2022 wheat growing season represents a typical dry season in the experiment location. Nevertheless, the 2021-2022 seasonal precipitation distribution (Fig 1B) demonstrated that dry conditions were observed in a particular period due to erratic rainfall patterns. Early in the season (Oct 1 – Nov 11, 2022), 122 mm of precipitation allowed appropriate winter wheat emergence and initial growth. This early season precipitation allowed stockpiled bermudagrass biomass to accumulate until the first killing frost, observed on Nov 2, 2021. Henceforward, dry soil conditions from Nov 12, 2021, to Feb 17, 2022, inhibited winter wheat biomass accumulation during late fall and early winter. Finally, precipitation resumed from Feb 28, 2022, allowing wheat biomass accumulation from late winter to mid-spring.

Figure 1C showcases the distribution of total precipitation during the bermudagrass season from 1994 to 2023. The total in-season bermudagrass precipitation amount (487 mm) for the year 2022 was slightly less (-8 mm) than the median value (495 mm) and located within the interquartile range. Thus, it did not particularly represent a dry or wet season in Perkins, OK; otherwise, it was a typical total precipitation for the bermudagrass season. However, the seasonal distribution revealed an erratic rainfall pattern, resulting in wet and dry periods within the 2022 bermudagrass season (Fig. 1D). Early in the season (i.e., May 1 - Jun 18, 2022), the precipitation accumulation represented more than 80% of the total seasonal precipitation (396 mm). This precipitation allowed good conditions for bermudagrass growth harvested on Jun 16, 2022 (first bermudagrass harvest).

After the first bermudagrass harvest, a lack of precipitation was observed until Jul 29, 2022, resulting in dry soil conditions and limited bermudagrass growth. Henceforth, a precipitation of 50 mm between Jul 20 and Aug 9, 2022, allowed bermudagrass growth for the second harvest on Aug 17, 2022. Towards the end of the bermudagrass season (from Aug 17 to Sep 11, 2022), an accumulation of 41 mm allowed good bermudagrass growth for a third and final bermudagrass harvest Set 14, 2022.

Total season biomass production

The total season biomass production (Nov. 2021 to Oct. 2022), i.e., the sum of all in-season harvested bermudagrass with stockpiled bermudagrass or wheat forage biomass according to each respective forage system, showed significant differences between cultivars ($p<0.01$) and forage systems ($p <0.01$); however, the interaction cultivar × forage systems ($p = 0.71$) was not significant (Table 1).

The total season biomass production for Tifton44 plots was greater than Midland and Ozark (Table 1). Midland99 plots had similar total season biomass production to all cultivar plots except for the greatest yielding (Tifton 44). Finally, Goodwell and Greenfield plots produced the least total seasonal biomass.

Comparing the evaluated forage systems, the greatest total season biomass production value was observed in plots interseeded with winter wheat (BER+WHEAT,

Table 1). In contrast, stockpiling bermudagrass for winter forage availability (BER+STOCK) had an intermediate total season biomass production. In-season bermudagrass cultivar plots, which were harvested only during the bermudagrass in-season and left fallow (BER) showed the lowest total season biomass production among forage systems.

Total in-season bermudagrass biomass

The total in-season bermudagrass biomass showed significant effects of cultivar and forage system ($P < 0.01$); however, the interaction between cultivar × forage systems ($P = 0.78$) was not significant.

Addressing the effect observed for cultivar, the total in-season bermudagrass production was greater for Tifton44 than for Midland99, Greenfield or Goodwell, but did not significantly differ from Midland and Ozark. Midland99 biomass production was similar to Ozark and Goodwell, and Greenfield had the lowest total in-season bermudagrass biomass production, differing from all cultivars except Goodwell.

All forage systems were different from each other in total in-season bermudagrass production. The BER forage system produced the greatest value (Table 1), followed by BER+WHEAT, with an intermediate production. The lowest total in-season bermudagrass biomass was observed in BER+STOCK, producing 2.37 Mg ha^{-1}.

Seasonal biomass production and nutritive value dynamics in each forage systems

Biomass production

The seasonal biomass production distribution throughout the season for each forage system showed significant effects of Forage Systems ($P < 0.01$); however, the interaction Cultivar × Forage systems ($P = 0.26$) was not significant.

On Dec 15, 2021, the observed stockpiled bermudagrass biomass in the BER+STOCK system plots were 1.50 Mg ha^{-1}. On the same date, forage wheat biomass was expected to be harvested in the BER+WHEAT system plots; however, as mentioned above, dry conditions hindered forage biomass production during fall and winter (Fig 1B). Nevertheless, thanks to early and mid-spring precipitations, winter wheat resumed growth, and 2.14 Mg ha^{-1} of forage wheat biomass was observed on Apr 29, 2022, in the BER+WHEAT plots.

Henceforth, bermudagrass started to break dormancy, aka green up, in mid-May, and all cultivars were first harvested on Jun 16, 2022. At first harvest, bermudagrass biomass at BER+STOCK showed the greatest values, followed by BER and BER+WHEAT systems. The latter two forage systems were considered statistically similar to each other and lesser than the former. The same trend was observed at the second harvest (Aug 17, 2022), when the bermudagrass biomass for BER+STOCK, BER, AND BER+WHEAT were 0.84, 0.81, and 0.79 Mg ha^{-1}, respectively. However, despite their numerical differences, the three systems were similar. Finally, BER and BER+WHEAT were similar at the third harvest (Sep 14, 2022). At this final harvest, the bermudagrass forage collection at BER+STOCK was postponed to December, i.e., stockpiled bermudagrass (data not shown).

Crude Protein

Crude protein was significantly affected by harvest events nested within forage systems ($P < 0.01$). The crude protein content from stockpiled bermudagrass biomass harvested on Dec 15, 2021, showed the least value, and differed from all other forages harvested on different days (Table 2). The winter wheat biomass harvest on Apr 29, 2022, showed intermediate CP content values, meaning greater than stockpiled bermudagrass and lesser than bermudagrass harvested at all forage systems and days. The only exception was bermudagrass harvested on Aug 17, 2022 (second harvest) at BER+STOCK forage systems, which showed similar CP values to winter wheat. Different CP content results were observed during the bermudagrass season. At first harvest (Jun 16, 2022), bermudagrass biomass presented the greatest CP content values at the BER+WHEAT forage system, followed by BER and BER+STOCK. At the second harvest (Aug 17, 2022), bermudagrass biomass at BER+WHEAT forage system had similar and greater CP content values than BER and BER+STOCK forge systems, respectively. Finally, the CP content reported for bermudagrass harvested at BER and BER+WHEAT plots were 15% and 15.9% and considered similar at the third harvest (Sep 14, 2022).

Detergent Fibers and lignin contents

Neutral detergent fiber, ADF, and ADL (lignin) showed significant effects of harvest events nested within forage systems ($P <0.01$). The stockpiled bermudagrass biomass showed the greatest NDF, ADF, and lignin content values, and conversely, the winter wheat biomass showed the lowest values.

Similar NDF, ADF, and lignin trends were observed during the bermudagrass season. Bermudagrass biomass collected at the first harvest presented the greatest NDF content values at BER+STOCK forage system, followed by BER and BER+WHEAT forage systems values. An identical numerical and slightly different statistical results were observed for ADF and lignin. Acid detergent fiber content at BER+STOCK and BER forage systems were similar to each other and greater than the BER+WHEAT forage systems value. Also, a lignin content of 4.7% was observed at both BER and BER+STOCK forage systems, which was greater than the BER+WHEAT forage system value.

The same trend was observed for ADF, NDF, and lignin at the second bermudagrass harvest. In-season + stockpiled bermudagrass forage system (BER+STOCK) showed bermudagrass biomass with the greatest ADF, NDF, and lignin values, which were not different from BER forage system values. Although the ADF, NDF, and lignin values were numerically the least at the BER+WHEAT forage system, they were similar to the two other forage systems values. Finally, not different from BER, with 30.8% for the first variable and 62.4% for the second. As mentioned, the third bermudagrass harvest was only performed at BER and BER+WHEAT forage systems. In-season bermudagrass forage system presented an ADF of 29.5%, NDF of 61.9%, and BER+WHEAT, an ADF of 28.5%, and an NDF of 60.1%.

In Vitro Dry Matter Digestibility 48 Hours

In vitro dry matter digestibility 48 hours significantly affected harvest events nested within forage systems ($P < 0.01$). The stockpiled bermudagrass and winter wheat biomass observed at BER+STOCK and BER+WHEAT forage systems presented the least (58.7%) and greatest (83.6%) IVTDMD48 content values, respectively. These extreme IVTDMD48 content values differed from each other, and from all in-season bermudagrass biomass collected at all forage systems and dates. Furthermore, the three forage systems' bermudagrass biomass IVTDMD48 content values differed at the in-season bermudagrass first harvest. In-season bermudagrass (BER) forage system produced biomass with an IVTDMD48 value of 71.3%, followed by BER+STOCK and BER+WHEAT forage systems with IVTDMD48 values of 68.2% and 75.4%, respectively. At the second harvest, the bermudagrass biomass IVTDMD48 content value at the BER+WHEAT forage system (74.1%) was numerically the greatest. Still, it differed only from the BER+STOCK forage system value (71.1%), the least IVTDMD48 content value. The intermediate IVTDMD48 content value (72.4%) observed in the BER forage system was similar to BER+WHEAT and BER+STOCK forage systems values. Finally, bermudagrass biomass IVTDMD48 content value at BER (75%) and BER+WHEAT (83.6%) forage systems differed.

Discussion

In-season bermudagrass interseeded with winter wheat (BER+WHEAT) forage system yielded the greatest total season biomass, followed by BER+STOCK and BER forage systems. A 43.7% and 38.76% increase in total season biomass production in BER+WHEAT and BER+STOCK was observed when compared to BER, respectively.

During the studied years, BER+WHEAT guaranteed four harvest events (three harvests during the bermudagrass season and one during the spring, Fig. 2A). However, a harvest during the winter was expected but did not occur. The reason is that the 2021 fall and early winter were dry (Fig. 1B), prohibiting winter wheat biomass accumulation and reducing winter harvest to only one harvest event during spring in BER+WHEAT. Nevertheless, BER+STOCK plots enabled four harvest events as expected, and, differently from BER+WHEAT, winter forage was harvested. Forage mass accumulation in BER+STOCK plots occurred before the condition's onset during the fall, from August 19, 2021, to November 11, 2021, allowing 85 days of bermudagrass growth.

The explanation for these different total season biomass results is that these two alternative forage systems to BER produced high amounts of biomass during winter (BER+STOCK) or during spring (BER+WHEAT), with minimal penalties to total in-season bermudagrass production. A total winter wheat forage production of 2.14 Mg ha^{-1} in late spring at the BER+WHEAT forage system, which is a 67.8% biomass increase when compared to total in-season bermudagrass biomass produced at the BER forage system (2.92 Mg ha^{-1}), was achieved by only reducing total in-season bermudagrass biomass production in 0.16 Mg ha^{-1} (2.92 minus 2.76 Mg ha^{-1}), which was a slight reduction of 5.5% reduction, 2.92 minus 2.76 Mg ha^{-1}). Moreover, 1.5 Mg ha^{-1} of stockpiled bermudagrass biomass was harvested in mid-December at the BER+STOCK systems plots, increasing by 32.5% of the total season biomass compared to the total in-season bermudagrass biomass produced at the BER forage system. However, this produced stockpiled biomass was by deferring the third in-season bermudagrass harvest to winter, affecting total in-season bermudagrass biomass production by decreasing 0.55 Mg ha^{-1} of it (2.92 minus 2.37 Mg ha^{-1}), a substantial reduction of 18.8%.

Although the 2021-2022 season was considered a median year for total precipitation during the bermudagrass season, the precipitation had an erratic distribution. Most precipitation (80.4%, 392 mm) occurred before the bermudagrass first harvest, allowing great amounts of bermudagrass biomass. Conversely, only 11.2% (54 mm) and 8.4% (41 mm) of the total rainfall occurred before the second and third bermudagrass harvests, respectively, allowing low forage mass accumulation.

A significant forage systems effect for in-season bermudagrass biomass production was observed only in the first bermudagrass harvest when BER+STOCK produced greater biomass than the others. This greater bermudagrass forage production is directly associated with the previous stockpiling event. During the stockpiling, bermudagrass enters the reproductive stage. Plants translocate nutrients from leaves and stems to the stolons, rhizomes, and roots at this stage. This nutrient translocation will occur until the first killing frost onset, when the phloem vascular tissue is disrupted, cutting nutrient flow to the stolons and other belowground structures (Larcher, 1981). Therefore, bermudagrass plants previously stockpiled will have greater nutrient amounts to survive the winter and resume growth, aka, green up, next summer compared to bermudagrass plants earlier harvested, such as BER+WHEAT and BER plants.

Moreover, a greater amount of water might be infiltrated into the soil from late summer to winter at BER+STOCK than the other systems. At this period, the stockpiled bermudagrass plots consisted of senescing plants with low transpiration rates and full canopy cover (minimal evaporation). In contrast, the BER system's soil was mainly exposed to solar radiation, resulting in evaporation, and the BER+WHEAT system's soil was not only exposed to solar radiation (evaporation) but also to new wheat seedling transpiration. Thus, the different management applied at each forage system from late summer to winter might have impacted bermudagrass regrowth differently in the following summer.

Stockpiled bermudagrass nutritive value was low, which can be associated with a combination of factors. As forage plants mature, they increase fiber content and decrease crude protein content (Ball et al., 2001; Buxton and Fales, 1994). Stockpiled bermudagrass was allowed to enter the reproductive stage, leading to a great decline CP and an increase in lignin content. The increase in lignin content explained the greater values for NDF, ADF, and lower IVTDMD48 content values. Finally, bermudagrass leaves typically have higher nutrient content than stems (Nelson & Moser, 1994; Griffin & Jung, 1983). During the stockpiling period, leaf shattering occurred due to plant senescence and wind, resulting in a greater stem-to-leaf ratio and, thus, lower forage nutritive value. For instance, based on Lalman & Holder (2023), the minimum required for steer and heifer calves to gain 0.23 kg per day is 9.2% for crude protein and 54% total digestible nutrients [TDN = 88.9 – (0.779*AADF)]. In-season + stockpiled bermudagrass (BER+STOCK) forage system performed inferior CP, not meeting the nutritional requirements of livestock, and suggesting that supplementation would be required. In contrast, BER+WHEAT and BER systems showed nutritional values superior to the minimum required to grow steer and heifer calves, excluding supplementation.

The differential fertility management among the BER, BER+WHEAT, and BER+STOCK systems could have significantly influenced the observed results in terms of both biomass production and nutritive values. Fertility levels play a critical role in plant growth, biomass accumulation, and nutritional content. For instance, higher fertility levels in BER+WHEAT might have contributed to the increased biomass compared to the other forage systems. Therefore, it is essential to consider the impact of fertility variations when interpreting the performance of these forage systems, as they could be key confounding factors influencing both yield and nutritive value. This aspect underscores the complexity of agricultural systems and the necessity for further investigations.

Conclusion

Interseeding winter wheat into bermudagrass can significantly extend forage production beyond the summer period with high nutritive value, reducing costs associated with animal supplementation. However, environmental factors, particularly precipitation, play a significant role in forage production dynamics and must be considered when opting for forage production systems. Interseeding winter wheat could add flexibility to the grazing system, increasing annual forage production and extending the grazing window, while stockpiling bermudagrass could provide winter forage availability dependent of supplementation.

Thus, the results revealed that each system had its pros and cons; therefore, we argued that producers must implement the three of them simultaneously and rotate them among the paddocks that compose their forage production system. With that, the three different systems would complement each other, and forge production would be possible in all seasons.

Expanding the study by incorporating an economic analysis is essential, as it would provide a comprehensive understanding of the cost-effectiveness of each forage production system.

REFERENCES

Adams, D. C., Clark, R. T., Coady, S. A., Lamb, J. B., & Kielson, M. K. (1994). Extended grazing systems for improving economic returns from Nebraska sandhills cow/calf operations. *Journal of Range Management, 47*, 258-263. https://doi.org/10.2307/4002544

Arnall, B., Jones, J. J., Pugh, B., Rocateli, A., Sanders, H., Warren, J., & Zhang, H. (2018). *Oklahoma forage and pasture fertility guide*. Oklahoma Cooperative Extension Service.

Baath, G. S., Northup, B. K., Rocateli, A. C., Gowda, P. H., & Neel, J. P. S. (2018). Forage potential of summer annual grain legumes in the Southern Great Plains. *Agronomy Journal*, *110*, 1–13. https://doi.org/10.2134/agronj2017.12.0726

Ball, D. M., Collins, M., Lacefield, G. D., Martin, N. P., Mertens, D. A., Olson, K. E., Wolf, M. W. (2001). Understanding forage quality. *American Farm Bureau Federation Publication, 1*(01), 1-15.

Ball, D. M., Frost, S. M., Tarasoff, C., & Mallory-Smith, C. (2005). Biology of rattail fescue and its management in direct-seeded winter wheat and chemical fallow. In

2005 Dryland Agricultural Research Annual Report. (pp. 92–103). Corvallis, OR: Agricultural Experiment Station, Oregon State University.

Ball, D. M., Hoveland, C. S., & Lacefield, G. D. (2002). *Southern Forages: Modern Concepts for Forage Crop Managemen*t *(3rd ed.).* Potash & Phosphate Institute and Foundation for Agronomic Research.

Ball, D. M., Hoveland, C.S., & Lacefield, G.D. (2007). *Southern Forages: Modern Concepts for Forage Crop Managemen*t (4th ed.). Potash & Phosphate Institute and the Foundation for Agronomic Research.

Ball, D. M., Hoveland, C. S., & Lacefield, G. D. (2015). *Southern forages: Modern concepts for forage crop management* (5th ed.). International Plant Nutrition Institute.

Barnes, R.F., Miller, D.A., & Nelson, C.J. (Eds.). (1999). *Forages: Vol. I. An Introduction to Grassland Agriculture* (6th ed., pp. 417-426). Iowa State University Press.

Barnes, R. F., Nelson, C. J., Moore, K. J., & Collins, M. (2007). *Forages: The Science of Grassland Agriculture*. *Volume II*. 6th ed. (pp. 289-302). Blackwell Publishing.

Beard, J. B. (1973). *Turfgrass: Science and culture*. Prentice Hall.

Brady, N.C., & Weil, R.R. (1996*). The nature and properties of soils* (11th ed.). Prentice-Hall.

Bu, L.-d., Liu, J.-l., Zhu, L., Luo, S.-s., Chen, X.-p., Li, S.-q., Hill, R. L., Zhao, Y. (2013). The effects of mulching on maize growth, yield and water use in a semi-arid region.

Agricultural Water Management, 123, 71-78. https://doi.org/10.1016/j.agwat.2013.03.015

Burton, G.W. (1954). *Coastal Bermuda grass*. Georgia Agricultural Experiment Station, Athens

Burton, G.W. (1993). African grasses. In J. Janick & J.E. Simon (Eds.). *New Crops* (pp. 294-298). Wiley.

Burton, G. W., Jackson, J. E., & Hart, R. H. (1963). Effects of cutting frequency and nitrogen on yield, in vitro digestibility, and protein, fiber, and carotene content of Coastal Bermudagrass. *Agronomy Journal*, *55(5),* 500. https://doi.org/10.2134/agronj1963.00021962005500050027x

Burton, G.W., Prine, G.M., & Jackson, J.E. (1957). Studies of drouth tolerance and water use of several southern grasses. *Agronomy Journal, 49.* 498-503. https://doi.org/10.2134/agronj1957.00021962004900090010x

Buxton, D.R., & Fales, S.L. (1994). Plant environment and quality for all treatments predicting GDD, CP and NDF. In G.C. Fahey et al. (ed.). *Forage quality, evaluation, and utilization. ASA*, CSSA, SSSA.

Callahan, L.M., & Engel, R.E. (1965). The effects of phenoxy herbicides on the physiology and survival of turfgrass. *Green Section Record, 3(1)*, 1-5.

Christians, N.E., Patton, A.J., & LQDQ.D. (2011). *Fundamentals of turfgrass management* (4th ed.). John Wiley and Sons.

Condon, A. G., Richards, R. A., Rebetzke, G. J., & Farquhar, G. D. (2004). Breeding for high water-use efficiency. *Journal of Experimental Botany, 55(407)*, 2447–2460. https://doi.org/10.1093/jxb/erh277

Connor, R. (Ed.). (2015). *The United Nations world water development report 2015: Water for a sustainable world* (Vol. 1). UNESCO publishing.

Double, R. L. (1996). *Turfgrasses, Their Management and Use in the Southern Zone*. Texas A&M University Pres.

Double, R.L. (2001). *Turfgrasses: Their Management and Use in the Southern Zone (2nd ed.)*. Texas A&M University Press.

Double, R.L. (n.a.). Bermudagrass: The Sports Turf of the South. Texas A&M University Press.

D'Souza,G. E., Maxwell, E. W., Bryan, W. B., & Prigge, E. C. (1990). Economic impacts of extended grazing systems. *American Journal of Alternative Agriculture, 5*, 120-125. https://doi.org/10.1017/S0889189300003428

Edwards, J., & Warren, J. (2017). *Sod-seeding small grains into bermudagrass pasture.* Oklahoma State University Extension. https://extension.okstate.edu/fact-sheets/sod-seeding-small-grains-into-bermudagrass-pasture.html

Franzluebbers, A. J. (2007). Integrated crop–livestock systems in the southeast USA. *Agronomy Journal, 99(2)*, 361–372. https://doi.org/10.2134/agronj2006.0136

Gamble, M.D., & Rhoades, E.D. (1964). Effect of shoreline fluctuations on grasses associated with upstream flood prevention and watershed protection. *Agronomy Journal, 56,* 21-23.

Ghannoum, O. (2009). C4 photosynthesis and water stress. *Annals of Botany, 103(5),* 635–644.

Griffin, J.L. & Jung, G.A. (1983). Leaf and Stem Forage Quality of Big Bluestem and Switchgrass. *Agronomy Journal, 75,* 723-726. https://doi.org/10.2134/agronj1983.00021962007500050002x

Guretzky, J. A., Ball, J., & Cook, B. J. (2008). Nitrogen fertilizer rate and weather dictate nutritive value of fall stockpiled bermudagrass. *Forage and Grazinglands*. https://doi.org/10.1094/FG-2008-0118-01-RS

Hatfield, J. L., & Dold, C. (2019). Water-use efficiency: Advances and challenges in a changing climate. *Frontiers in Plant Science, 10,* 103. https://doi.org/10.3389/fpls.2019.00103

Hitz, A. C., & Russell, J. R. (1998). Potential of stockpiled perennial forages in winter grazing systems for pregnant beef cows. *Journal of Animal Science, 76*, 404–415.

Hoppe, K., & Tobin, C. (2023). *Feeding wheat to beef cattle.* NDSU Extension. https://www.ndsu.edu/agriculture/sites/default/files/2023-06/as1184_2023.pdf

Howard, C.W. (1881). *Manual of cultivated grasses and forage plants of the south.* James Harrison, Atlanta.

Hu, Z., Huang, X., Amombo, E., Liu, A., Fan, J., Bi, A., Ji, K., Xin, H., Chen, L., & Fu, J. (2020). The ethylene responsive factor CdERF1 from bermudagrass (Cynodon dactylon) positively regulates cold tolerance. *Plant Science, 294*, 110432. https://doi.org/10.1016/j.plantsci.2020.110432

Karlen, D. L., Wollenhaupt, N. C., Erbach, D. C., Berry, E. C., Swan, J. B., Eash, N. S., & Jordahl, J. L. (1994). Crop residue effects on soil quality following 10 years of no-till corn. *Soil and Tillage Research, 31(2–3),* 149-167. https://doi.org/10.1016/0167-1987(94)90077-9

Kim, K.S., & Beard, J.B. (1988). Comparative turfgrass evapotranspiration rates and associated plant morphological characteristics. *Crop Science, 28,* 328-331.

Kim, C., Lemke, C., & Paterson, A.H. (2009). Functional dissection of drought-responsive gene expression patterns in Cynodon dactylon L. *Plant Molecular Biology, 70*, 1–16.

Lalman, D., & Highfill, G. (2017). *Feeding high quality, low test weight and sprouted wheat.* OSU Extension. https://extension.okstate.edu/fact-sheets/feeding-high-quality-low-test-weight-and-sprouted-wheat.html

Lalman, D., & Holder, A. (2023). *Nutrient Requirements of Beef Cattle.* OSU Extension. https://extension.okstate.edu/fact-sheets/print-publications/e/nutrient-requirements-of-beef-cattle-e-974.pdf

Lalman, D. L., Taliaferro, C. M., Epplin, F. M., Johnson, C. R., & Wheeler, J. S. (2000). Review: Grazing stockpiled bermudagrass as an alternative to feeding harvested forage. *Journal of Animal Science, 79,* 1. https://doi.org/10.2527/jas.00.079es1001h

Lalman, D., Woods, B., Barnes, K., Readfearn, D., & Coffey, C. (2017). *Managing bermudagrass pasture to reduce winter hay feeding in beef cattle operation.* OSU Extension. https://extension.okstate.edu/fact-sheets/managing-bermudagrass-pasture-to-reduce-winter-hay-feeding-in-beef-cattle-operations.html

Larcher, W. (1981). *Effects of low temperature stress and frost injury on plant productivity*. Physiological processes limiting plant productivity, 253-269.

Leakey, A. D. B., Ferguson, J. N., Pignon, C. P., Wu, A., Jin, Z., Hammer, G. L., & Lobell, D. B. (2019). Water use efficiency as a constraint and target for improving the resilience and productivity of C3 and C4 crops. *Annual Review of Plant Biology, 70*, 781–808. https://doi.org/10.1146/annurev-arplant-042817-040305

Lesley, A.R. (1994). *Handbook of integrated pest management for turf and ornamentals (1st ed)* CRC Press. https://doi.org/10.1201/9780138752798

Lollato, R. P., Marburger, D., Holman, J. D., Tomlinson, P., Presley, D., & Edwards, J. T. (2017). *Dual purpose wheat: Management for forage and grain production.* OSU Extension. https://extension.okstate.edu/fact-sheets/dual-purpose-wheat-management-for-forage-and-grain-production.html

Marsalis, M. (2018). *Small grain forages for New Mexico*. New Mexico State University. https://aces.nmsu.edu/pubs/_circulars/CR630/welcome.html

Marschner, P. (Ed.). (2012). *Marschner's mineral nutrition of higher plants (3rd ed.).* Elsevier/Academic Press.

Martin, N. P., Russelle, M. P., Powell, J. M., Sniffen, C. J., Smith, S. I., Tricarico, J. M., & Grant, R. J. (2017). Invited review: Sustainable forage and grain crop production for US dairy industry. *Journal of Dairy Science, 100(12),* 9479–9494. https://doi.org/10.3168/jds.2017-13080

Matches, A. G., & Burns, J. C. (1985). Systems of grazing management. In M. E. Heath, R. F. Barnes, & D. S. Metcalfe (Eds.), *Forages – The science of grassland agriculture* (pp. 537-547). Iowa State University Press.

Mays, D. A., & Washko, J. B. (1960). The feasibility of stockpiling legume-grass pasture. *Agronomy Journal, 52(3)*, 190-192.

McCarty, L. B., & Miller, G. L. (2002). *Managing Bermudagrass Turf: Selection, Construction, Cultural Practices, and Pest Management Strategies.* John Wiley & Sons.

McCurdy, J. D., Flournoy, E. T., Stewart, B. R., Philey, H. W., Reddy, K. R., Kreuser, W. C., Reasor, E., & Baldwin, C. M. (2020). Estimates of Turf-Type Hybrid Bermudagrass Base and Optimal Growth Temperatures. Journal of the Mississippi *Academy of Sciences, 65(3),* 258-268. https://msacad.org/wp-content/uploads/2013/04/July-2020_Vol65_No-3.pdf

McPherson, R. A., Fiebrich, C. A., Crawford, K. C., Kilby, J. R., Grimsley, D. L., Martinez, J. E., Kloesel, K. A. (2007). Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet. *Journal of Atmospheric and Oceanic Technology, 24*(3), 301-321.

Min, B. R., Pinchak, W. E., Fulford, J. D., & Puchala, R. (2005). Wheat pasture bloat dynamics, in vitro ruminal gas production, and potential bloat mitigation with condensed tannins. *Journal of Animal Science, 83(6),* 1322–1331. https://doi.org/10.2527/2005.8361322x

Mirabile, M., Bretzel, F., Gaetani, M., Lulli, F., & Volterrani, M. (2016). Improving aesthetic and diversity of bermudagrass lawn in its dormancy period. *Urban Forestry & Urban Greening, 18,* 190-197. https://doi.org/10.1016/j.ufug.2016.06.007

Morison, I. L., Baker, N. R., Mullineaux, P. M., & Davies, W. J. (2008). Improving water use in crop production. Philosophical Transactions of the R*oyal Society B: Biological Sciences*, *363*, 639–658.

Moser, L.E., Burson, B.L., & Sollenberger, L.E. (Eds.). (2004). Warm-season (C4) Grasses *Agronomy Monographs No. 45*, pp. 1-14.

Nelson, C.J. & Moser, L.E. (1994). Plant Factors Affecting Forage Quality. In G.C. Fahey (Ed.). *Forage Quality, Evaluation, and Utilization*. (15-ASA, CSSA, SSSA. https://doi.org/10.2134/1994.foragequality.c3

NRCS. (2008). Official soil series descriptions. USDA Natural Resources Conservation Service.

Oklahoma Department of Agriculture, Food and Forestry. (2021). *Oklahoma Agriculture Statistics Pocket Facts.* https://www.nass.usda.gov/Statistics_by_State/Oklahoma/Publications/Annual_Statistical_Bulletin/ok-pocket-facts-2021.pdf

Owens, F. N., Secrist, D. S., Hill, W. J., & Gill, D. R. (1998). Acidosis in cattle: A review. *Journal of Animal Science, 76(1)*, 275–286. https://doi.org/10.2527/1998.761275x

Pereira, J. S., Chaves, M. M., Caldeira, M. C., & Correia, A. V. (2007). Water availability and productivity. In J. I. L. Morison, & M. D. Morecroft, (Eds.), *Plant growth & climate change* (pp. 118–145). Blackwell Publishing.

Rankins, D. L., & Pugh, D. G. (2012). Nutrition and feeding of sheep and goats. In D. G. Pugh & A. N. Baird (Eds.), *Sheep and Goat Medicine* (2nd ed., pp. 21-40). Elsevier Health Sciences.

Redfearn, D., Arnall. B., Zhang, H., Rice, C. (2016). Fertilizing Bermudagrass Hay and Pasture. OSU Extension. https://extension.okstate.edu/fact-sheets/fertilizing-bermudagrass-hay-and-pasture.html

Redmon, L. A. (2002). *Forages for Texas*. Texas A&M AgriLife Extension. http://forages.tamu.edu/PDF/scs2002-14.pdf

Rocateli, A.C., Abreu, L.F., Horn, K.M. (2019). *Oklahoma Bermudagrass Variety Performance Tests 2016-2018 Forage Year.* OSU Extension. https://extension.okstate.edu/fact-sheets/oklahoma-bermudagrass-variety-performance-tests-2016-2018-forage-years.html

Rocateli, A.C., & Abreu, L.F., (2020). *Oklahoma Bermudagrass Variety Performance Tests 2019 Forage Year.* OSU Extension. https://extension.okstate.edu/fact-sheets/oklahoma-bermudagrass-variety-performance-tests-2019-forage-year.html

Rohweder, D. A., Barnes, R. F., & Jorgensen, N. (1978). Proposed hay grading standards based on laboratory analyses for evaluating quality. *Journal of Animal Science, 47*(3), 747–759. https://doi.org/10.2527/jas1978.473747x

Sadras, V.O., & Angus, J.F. (2006). Benchmarking water-use efficiency of rainfed wheat in dry environments. *Aust. J. Agric. Res., 57*(8), 847–856.

Silva, A. O., Lynch, T., Cyrineu, I. M., Olaniyi, S. A., Stowers, C., & Crabtree, L. (2023). *Fall forage production and first hollow stem date for wheat varieties during the 2022-2023 crop year.* https://extension.okstate.edu/fact-sheets/print-publications/cr/fall-forage-production-and-first-hollow-stem-date-for-wheat-varieties-during-the-2022-2023-crop-year-a.pdf

Silva, A. O., Stowers, C., Swantek, T., Lynch, T., Muyombo, E., Cyrineu, I. M., & Crabtree, L. (2022). *Fall forage production and first hollow stem date for wheat varieties during the 2021-2022 crop year.* https://extension.okstate.edu/fact-sheets/fall-forage-production-and-first-hollow-stem-date-for-wheat-varieties-during-the-2021-2022-crop-year.html

Stanhill, G. (1986). Water use efficiency. *Advances in Agronomy, 39*, 53-85.

Tabak, M., Lepiarczyk, A., Filipek-Mazur, B., & Lisowska, A. (2017). The efficiency of nitrogen fertilization of winter wheat depending on sulfur fertilization. *Agronomy, 10*(9), 1304. https://doi.org/10.3390/agronomy10091304

Taliaferro, C. M. (1995). Diversity and vulnerability of Bermuda turfgrass species. *Crop Science, 35*, 327–332.

Taliaferro, C.M. (2003). Bermudagrass. In M.D. Casler & R.R. Duncan (Eds.), *Turfgrass biology, genetics, and breeding* (pp. 235-256). Wiley.

Taliaferro, C. M., Coleman, S. W., & Claypool, P. L. (1987). Relative winter forage quality of selected bermudagrass cultivars. *Crop Science*, *27*, 1285–1290.

Taliaferro, C.M., Rouquette, F.M., Jr., & Mislevy, P. (2004). Bermudagrass and Stargrass. In L.E. Moser, B.L. Burson, & L.E. Sollenberger (Eds.), *Warm-Season (C4) Grasses*. https://doi.org/10.2134/agronmonogr45.c12

Trenholm, L.E., Carrow, R.N., & Duncan, R.R. (2001). Wear Tolerance, Growth, and Quality of Seashore Paspalum in Response to Nitrogen and Potassium. *HortScience*, *36*(4), 780-783. https://doi.org/10.21273/HORTSCI.36.4.780

Ullah, H., Santiago-Arenas, R., Ferdous, Z., Attia, A., & Datta, A. (2019). Improving water use efficiency, nitrogen use efficiency, and radiation use efficiency in field crops under drought stress: A review. In D. L. Sparks (Ed.*), Advances in Agronomy* (Vol. 156, pp. 109-157). Academic Press. https://doi.org/10.1016/bs.agron.2019.02.002

USDA-NASS. (2019). *Annual cattle review*. USDA-NASS https://www.nass.usda.gov/Statistics_by_State/Oklahoma/Publications/Recent_Reports/2022/ok-cattle-review-2022.pdf

Webster, J. E., Hogan, J. W., & Elder, W. C. (1965). Effect of rate of ammonium nitrate fertilization and time of cutting upon selected chemical components and the in vitro rumen digestion of bermudagrass forage. *Agronomy Journal, 57*, 323–325.

Zhang, H., & Henderson, K. (2016). *Procedures Use at OSU Soil, Water, and Forage Analytical Laboratory*. OSU Extension. https://extension.okstate.edu/fact-sheets/procedures-used-by-osu-soil-water-and-forage-analytical-laboratory.html

Zhang, J., Richardson, M., Karcher, D., McCalla, J., Mai, J., & Luo, H. (2021). Dormant sprigging of bermudagrass and zoysiagrass. *HortTechnology, 31*(4), 395-404. https://doi.org/10.21273/HORTTECH04763-20

Zhao, Y., Du, H., Wang, Z., & Huang, B. (2011). Identification of proteins associated with water-deficit tolerance in C4 perennial grass species, Cynodon dactylon×Cynodon transvaalensis and Cynodon dactylon. *Physiologia Plantarum*, *141*, 40–55. https://doi.org/10.1111/j.1399-3054.2010.01419.x

Table 1. Total season forage biomass harvested from mid-December 2021 to mid-September 2022 and total in-season bermudagrass biomass from mid-June to mid-September 2022 averaged by Cultivars and Forage Systems effects in Perkins, OK.

Season 2021-2022	**Total season biomass**	**Total in-season bermudagrass biomass**
Effects:	Mg ha^{-1}	Mg ha^{-1}
Cultivar		
Goodwell	3.63cd	2.36cd
Greenfield	3.39d	2.23d
Midland	4.21ab	2.98ab
Midland99	3.75bcd	2.65bc
Ozark	4.08abc	2.82ab
Tifton44	4.32a	3.06a
Forage Systems		
In-season bermudagrass (BER)	2.92c	2.92a
BER + stockpiled bermudagrass	3.87b	2.37c
BER interseeded with winter wheat	4.90a	2.76b
Type 3 test of Fixed Effects:	**p-value**	**p-value**
Cultivar	<0.01*	<0.01*
Forage systems	<0.01*	<0.01*
Cultivar × Forage Systems	0.71	0.78

[a, b, c, d] Letters denoted significant differences within columns and effects at the P-value listed.

[*] Significant at 95% confidence interval.

[a, b, c, d] Letters denoted significant differences within effects at the P-value listed.

[*] Significant at 95% confidence interval.

Table 2. Crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), acid detergent lignin (ADL), and in vitro dry matter digestibly 48 hours (IVTDMD48) averaged by Cultivar effect each harvest event from mid-December 2021 to mid-September 2022 in Perkins, OK.

		Season 2021 - 2022				
Perkins, OK	**Harvest date**	**CP**	**ADF**	**NDF**	**ADL**	**IVTDMD48**
Effects		%	%	%	%	%
Forage Systems						
BER + stockpiled bermudagrass						
Stockpiled bermudagrass	Dec 15, 2021	6.3h	40.7a	72.4a	5.9a	58.7g
Bermudagrass Harvest 1	Jun 16. 2022	10.6g	35.3b	65.7b	4.7b	68.2f
Bermudagrass Harvest 2	Aug 17, 2022	12.0ef	32.7c	65.1b	4.4bc	71.1e
BER + interseeded with winter wheat						
Winter wheat	Apr 29, 2022	11.2fg	25.0g	48.7f	2.1f	83.6a
Bermudagrass Harvest 1	Jun 16. 2022	14.5bc	32.2cd	60.4de	3.8e	75.4bc
Bermudagrass Harvest 2	Aug 17, 2022	13.7cd	30.8de	62.4cd3	4.0de	74.1cd
Bermudagrass Harvest 3	Sep 14, 2022	15.9a	28.5f	60.1e	4.0de	77.3b
In-season bermudagrass (BER)						
Bermudagrass Harvest 1	Jun 16. 2022	12.8de	34.6b	62.9c	4.7b	71.3e
Bermudagrass Harvest 2	Aug 17, 2022	12.8de	31.9cd	63.8bc	4.3cd	72.4de
Bermudagrass Harvest 3	Sep 14, 2022	15.0ab	29.5ef	61.9cde	4.2cd	75.0c
Type 3 test of Fixed Effects:		***P*-value**	***P*-value**	***P*-value**	***P*-value**	***P*-value**
Forage System		<0.01*	<0.01*	<0.01*	<0.01*	<0.01*
Cultivars		<0.01*	0.23	<0.01*	0.05	<0.01*
Forage Systems × Cultivar		0.69	<0.01*	0.64	0.20	0.51

$^{a\ b,\ c,\ d,\ e,\ f,\ g,\ h}$ Letters denoted significant differences within columns effects at the P-value listed.

*Significant at 95% confidence interval

Figure 1. (A) Boxplot denoting total precipitation distribution from 1994 to 2023 during stockpiled bermudagrass and winter wheat growing seasons (October 1 – April 29). (B) 2021 – 2022 Winter wheat and stockpiled bermudagrass season daily precipitation (C) Boxplot denoting total precipitation distribution from 1994 to 2023 during the bermudagrass growing season (May 1 – September 30). (D) 2022 bermudagrass growing season daily precipitation for Perkins, OK. The growing seasons evaluated in the experiment are shown as star and bold dot symbols for reference.

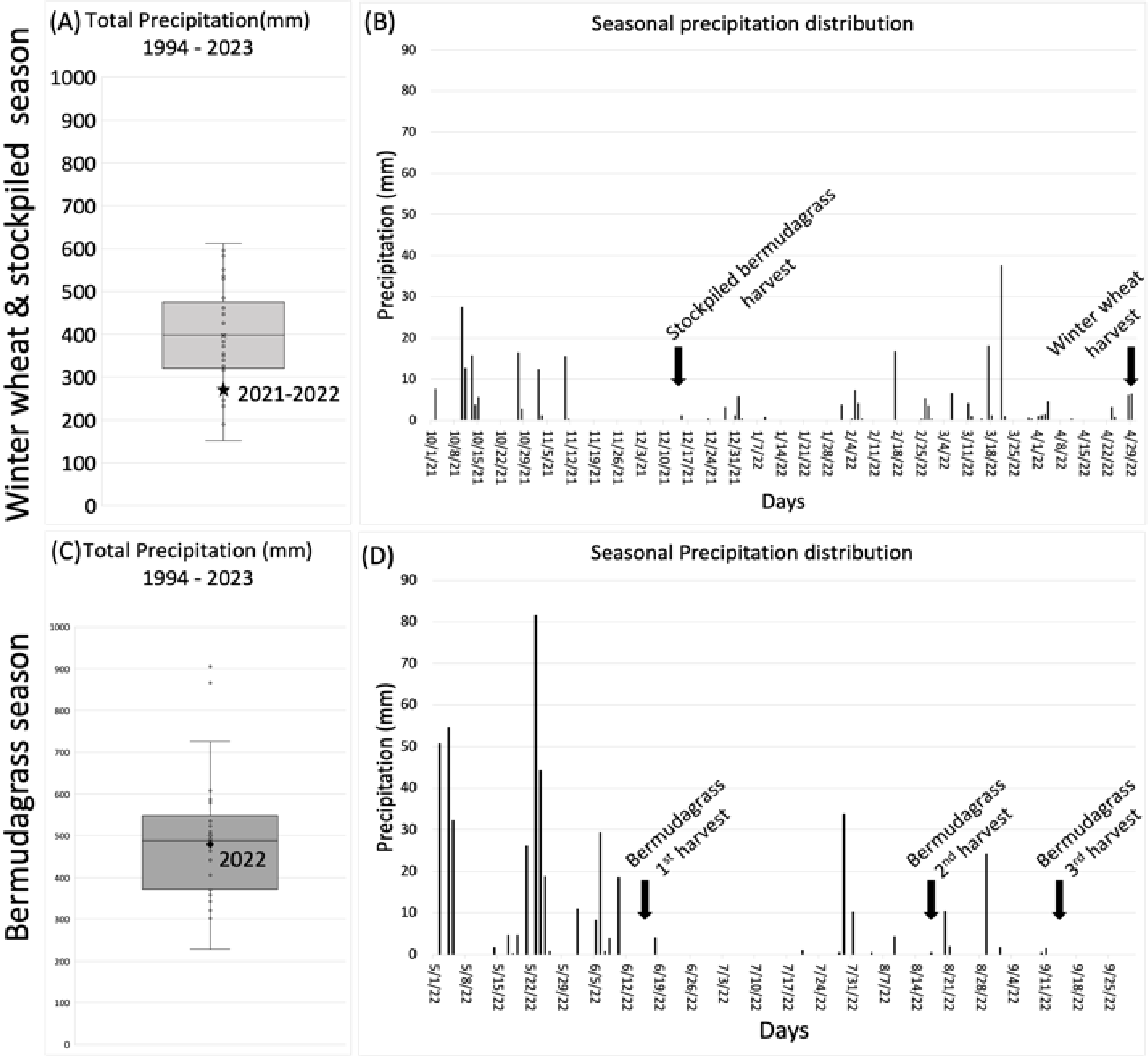
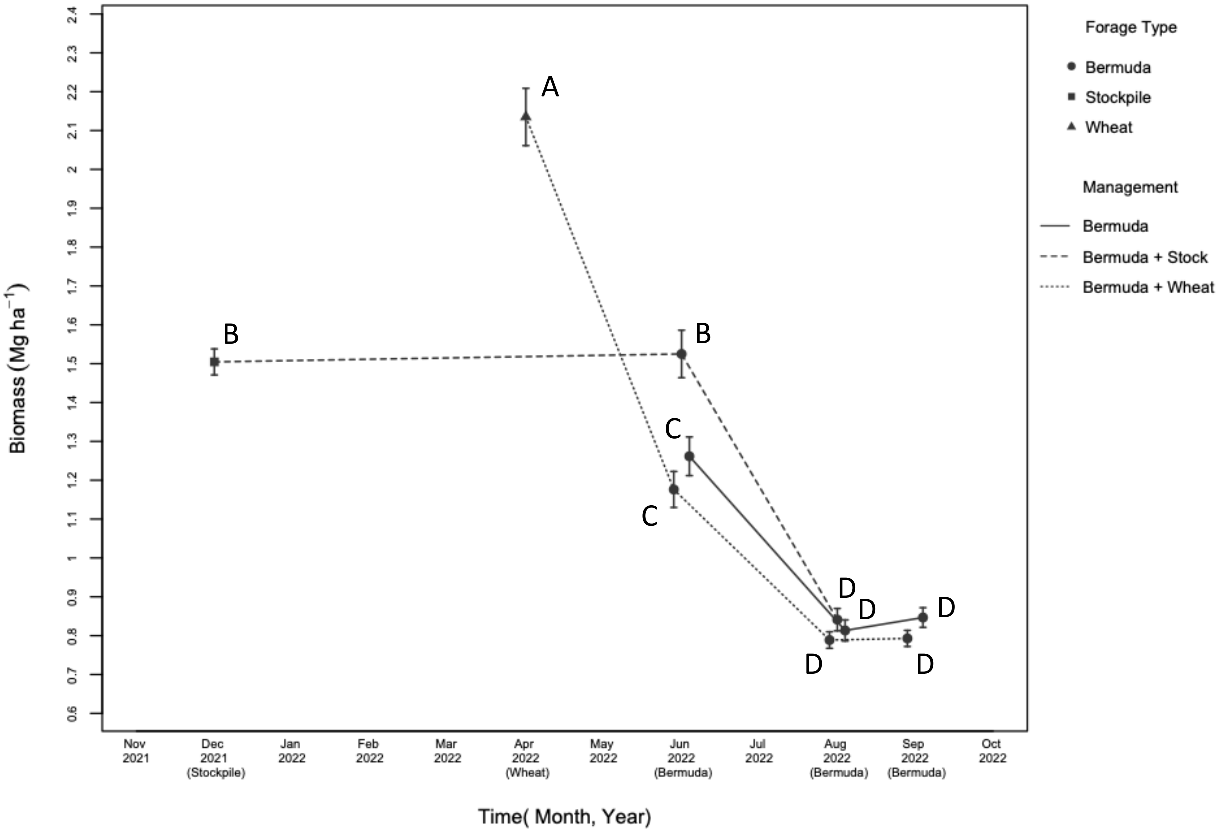


Figure 2. Forage biomass produced each harvest from mid-December 2021 to mid-September 2022 for Perkins, OK. Different line patterns denote different forage systems, and different symbols denote the average biomass production for a specific forage type at a harvest event.



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