

EVALUATION OF PEARL MILLET FOR FORAGE-FINISHED BEEF PRODUCTION
SYSTEMS

by

ROBERT WERNER McKEE

(Under the Direction of Alexander M. Stelzleni)

ABSTRACT

A three-year grazing trial was conducted to evaluate pearl millet [*Pennisetum glaucum* (L.) R.Br. (PM)] and brown-midrib pearl millet (BMR) with and without supplementation of soybean [*Glycine max* (L.) Merr.] hulls (0.75% of body weight (BW); PM+S and BMR+S, respectively) in a forage-finished beef production system in the southeastern U.S. Sixteen 0.81-ha pastures were randomly assigned to one of four finishing treatments in a completely randomized, 2x2 factorial design. Each year, Angus-cross bred steers ($n = 32$; 3-yr average BW = 439 ± 75 kg) were randomly assigned to treatment and finished for 64, 90, and 84 d during the summers of 2016, 2017, and 2018, respectively. Forage nutritive value samples and estimates of forage mass were taken at initiation, termination, and every two weeks throughout the grazing trial. Average daily gain (ADG) was calculated from fasted weights taken at grazing initiation and termination. Steers were harvested in September of each year and carcass data were collected 24 h postmortem. Striploins were removed from the right side of each carcass, vacuum packed, and allowed to age for 21 d. Striploins were fabricated into 2.54-cm steaks and allocated to meat quality and simulated retail display analyses. All data were analyzed using PROC GLIMMIX in SAS v. 9.4. All data from 2016 were omitted due to a lack of pearl millet in

treatment pastures. Treatments had no effect ($P > 0.05$) on forage mass. No differences ($P > 0.05$) were observed for relative forage quality and total digestible nutrients and forage variety had no effect ($P > 0.05$) on animal performance, hot carcass weight, dressing percent, nor ribeye area. However, supplemented steers exhibited greater ($P < 0.001$) ADG than non-supplemented steers. Slight differences ($P = 0.0278$) were observed for carcass lean L* values which were reflected in lean maturity and color ($P = 0.0234$ and $P = 0.0361$, respectively). No other treatment differences ($P > 0.05$) were observed. Results indicate pearl millet is a viable forage option for forage-finished beef systems and soybean hull supplementation improves animal performance over forage alone with minimal impacts on carcass characteristics, meat quality, and retail characteristics.

INDEX WORDS: Forage-finished beef, pearl millet, soybean hulls, warm-season annual forages

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B.S., Auburn University, 2013

M.S., Auburn University, 2015

A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial
Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2021

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May 2021

ACKNOWLEDGEMENTS

I would like to thank my major professor Dr. Stelzleni and my committee, Drs. Hancock, Stewart, and Calloway, for their guidance and patience over the past four years. The knowledge they have instilled in me is an invaluable resource I will use for the rest of my life. I would also like to thank my peers and colleagues for their assistance and encouragement during the completion of this degree. Lastly, I want to thank my family and friends for their support and understanding over the course of my education.

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CHAPTER 1

INTRODUCTION

There is growing consumer demand in the United States for locally produced, forage-finished beef products and consequently, growing producer interest in forage-finished beef production systems (Matthews and Johnson, 2013; Cheung et al., 2017). Forage-finished beef is traditionally a seasonal product with producers relying on highly digestible, cool-season forages rich in nutrient content to meet the demands of finishing cattle (Lozier et al., 2004). A more consistent and constant supply of fresh, forage-finished beef requires production and utilization of forages rich in nutrient content year-round (Harmon et al., 2019). In the southeastern U.S., long growing seasons allow for near year-round forage production; however, the warm-season perennial grasses common to southeastern pastures such as bermudagrass [*Cynodon dactylon* (L.) Pers.] and bahiagrass (*Paspalum notatum* Flügge), are often insufficient in nutritional content (crude protein and total digestible nutrients) and digestibility for finishing beef cattle (Schmidt et al., 2013). Several warm-season annual grasses are superior in nutritional content and digestibility to these warm season perennial grass species and therefore may offer producers a viable forage option for finishing beef cattle in southeastern U.S. during the summer months (Hill et al., 1999).

Pearl millet [*Pennisetum glaucum* (L.) R.Br.] is a warm-season annual grass native to Africa. Several varieties of pearl millet have been developed with a focus on improving dry matter yields, regrowth following defoliation, drought tolerance, and nutritive value (Andrews et al., 1993; Gulia et al., 2007). The brown mid-rib (BMR) trait has been selected for in several forage and silage crop species including corn (*Zea mays*), forage sorghum (*Sorghum* spp.), pearl millet, and sorghum-sudan hybrids (*Sorghum x drummondii*) (Christensen and Rasmussen, 2019). The BMR genetic mutation results in a reduction of lignin polymerization, increasing digestibility and nutritive value (Kuc and Nelson, 1964; Porter et al., 1978; Cherney et al., 1988). Nonetheless, comparisons of BMR and non-BMR pearl millet in a forage-finished beef production scenario are absent from the literature.

Soybean [*Glycine max* (L.) Merr.] hulls are a readily available and inexpensive by-product feed that is often used in cattle rations as sources of crude fiber and energy (Hsu et al., 1987; Kunkle et al., 2000). Supplementation of animals on pasture has shown to improve animal performance and decrease the length of the finishing period while continuing to utilize forage resources (Hoveland and Anthony, 1977; Anderson et al., 1988). Previous studies have shown improvements in fiber digestibility and dry matter intake when ruminant animals consuming grass hay were fed low amounts of soybean hulls (Grigsby et al., 1992; Canonenco de Araujo et al., 2008). To date, little research has been conducted to evaluate pearl millet and soybean hulls feeding in beef cattle forage-finishing systems.

There exists opportunity for forage-finished beef production in the southeastern U.S. During the summer months, maintaining adequate levels of animal performance for finishing beef cattle requires forages high in nutritive value, such as pearl millet. Furthermore,

supplementation with soybean hulls to grazing animals can increase animal performance over forage alone. However, variables crucial to determining the suitability of BMR and non-BMR pearl millet with soybean hull supplementation to forage-finished beef production, such as dry matter yields and nutritive value, animal performance, carcass characteristics, and meat quality, have yet to be reported in the literature. Therefore, the objective of this study was to examine pearl millet and BMR pearl millet with and without soybean hull supplementation for use in forage-finished beef production systems in the southeastern U.S.

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CHAPTER 2

REVIEW OF LITERATURE

Introduction

The United States is the leading beef producer in the world, generating 12.21 billion kg of beef in 2018 (USDA-AMS, 2019), and accounts for approximately 19% of U.S. agriculture sales at a value of \$76.4 billion (USDA, 2015). Beef cattle production in the U.S. is a segmented industry. Cow-calf production and stocker operations dominate the Southeastern cattle industry while a majority of the calves produced in this region are shipped to feedlots in the Midwest for finishing on grain-based diets. The development of this segmented production regime occurred due to availability of resources, differences in climate, consumer demand, efficiency, economic viability, and consistency in the ultimate beef product (Hoveland and Anthony, 1977; Matthews and Johnson, 2013).

The southeastern U.S. has long growing seasons and an abundance of marginal lands that are well-suited to forage production and grazing-based, cow-calf operations (Ball et al., 2015). The Midwestern U.S. is characterized by millions of hectares of fertile, arable land commonly referred to as the Corn Belt. This region earned this moniker from its ability to yield billions of

bushels of corn grain (*Zea mays* L.) per annum, of which about 10 percent is fed to beef cattle in concentrated beef finishing operations commonly referred to as feedlots (Hatfield, 2012). The beef product produced in this manner is high-quality and uniform due to large amounts of intramuscular fat or marbling, average animal age at slaughter less than two years resulting from rapid growth rate, and consistency in diet, production protocols, and, increasingly, genetics (Garmyn et al., 2010). While a majority of consumers are accustomed to and prefer grain-finished beef, forage-finished beef is a growing market sector due to perceived health benefits, concerns over animal welfare, and environmental issues (USDA-AMS, 2007).

Forage-Finished Beef

Forage-finished beef production utilizes roughages rather than grains as the only source of nutrients during the finishing period (USDA-FSIS, 2019). Forage-fed and forage-finished beef were much more common in the United States prior to World War II (Martin and Rogers, 2004). In the second half of the twentieth century, technological advancements in agriculture such as mechanization and chemical fertilizers spurred rapid increases in United States corn yields (Dimitri et al., 2005). As corn availability increased and prices dropped, increasing numbers of cattle were finished on corn-based rations rather than forages. The result was a more efficient production system that utilized less land while increasing animal rate of gain and improving meat quality. This production method and the resulting meat product eventually became the norm and consumers grew accustomed to the well-marbled, mild-flavored, and tender beef they found in abundance in butcher shops and grocery stores.

Forage-based beef production systems often yield inconsistent, lower-quality meat when compared with grain-finished beef production systems. This discrepancy is attributed to reduced nutrient density and greater variability in the forage-based diets often resulting in increased animal age at slaughter as well as reduced intramuscular fat content of forage-finished beef when compared with grain-finished beef (Minson, 1990; Duckett et al., 2009). Nonetheless, consumer demand for forage-finished beef is growing, largely due to the perceived health benefits arising from altered fatty acid profiles in the meat as well as apparent reductions in environmental impact and improvements in animal welfare touted by forage-based beef production advocates (USDA, 2007; Duckett et al., 2013).

Forage-finished beef contains less saturated fatty acids such as myristic acid (C14:0) and palmitic acid (C16:0), which have been associated with increased serum cholesterol in human consumers, than in grain-finished beef. Additionally, forage-finished beef exhibits greater concentrations of the healthier, mono- and polyunsaturated fatty acids (PUFA) such as conjugated linoleic acids (CLA) as well as decreased ratios of linoleic and linolenic fatty acids (n-6: n-3) than grain-finished beef (Realini et al., 2004; Leheska et al., 2008; Daley et al., 2010).

Growing consumer interest in locally sourced and sustainable food contributes to the increase in demand for forage-finished beef (Darby et al., 2006; Lacy et al., 2007). Forage-fed beef sales in the U.S. have grown from \$17 million in 2012, to \$272 million in 2016, to \$480 million in 2018. Ironically, a vast majority—75 to 80% of total sales—of the forage-fed beef consumed in the U.S. is imported. This is due, in part, to the ability to label an imported meat product “Product of the USA” as long as it has passed through a U.S. Department of Agriculture inspected facility, a requirement for all imported meat (Cheung et al., 2017; USDA-FSIS, 2017).

Despite this confusion, the large market sector occupied by imported forage-finished beef represents an opportunity for domestic beef producers.

The benefits of forage-finished beef and associated production systems are up for debate; however, consumer demand for beef produced in a forage-based system warrants further research and development of the production system (Cox et al., 2006). Furthermore, the several reports of consumers' willingness to pay a premium for locally-sourced, forage-finished beef and the large import market for forage-finished beef is indicative of economic opportunity for U.S. beef producers (Cox et al., 2006; Darby et al., 2006; Lacy et al., 2007).

Several studies have compared forage- and grain-finished beef and the associated production systems and found differences and similarities based on several criteria. Animal performance, efficiency, carcass characteristics, meat quality attributes and chemical content, consumer preference and acceptance, and the associated economic and environmental implications are some of the many metrics by which forage- and grain-finished beef have been compared (Schaake et al., 1993; Mandell et al., 1998; Cox et al., 2006; Leheska et al., 2008; Daley et al., 2010; Scaglia et al., 2012; Van Elswyk and McNeill, 2014). Regardless of this wealth of literature, it is challenging to isolate the effects of finishing diet on carcass characteristics and meat quality attributes as they are often confounded with time on treatment and or slaughter weight due to the vast discrepancies in nutritional content of forage- and grain-based diets (Muir et al., 1998). Additionally, determining economic and environmental impact of these two production systems has proven to be difficult due to the numerous variables at play.

Forages

Forages, mostly comprised of cellulosic biomass, comprise a significant portion of cattle diets in the U.S., particularly in the Southeast. Cattle are ruminant animals, capable of digesting fibrous feeds via a symbiotic relationship with microorganisms that inhabit a pre-gastric paunch called the rumen. Forages are required for proper rumen function and the well-being of cattle due to a long, evolutionary relationship between grazing animals, ruminant microorganisms, and forages (Van Soest, 1982). Forages are an economical nutrient source for cattle as they are inherently low-input and are often grazed, that is, harvested by the animal rather than by machinery, saving on infrastructure and labor costs (Wright, 2005). As a result, the economic viability of the cattle industry is largely dependent on forage production. This is especially true in the southeastern U.S., which is covered by an estimated 34 million ha of perennial and annual forages (Ball et al., 2015). When compared with other feedstuffs utilized by the livestock industries, forages are the most variable in terms of nutritional value and production as these variables are affected by forage species and variety, soil fertility, stage of growth, management, and several other factors (Allen, 1996).

Forages can be classified into four distinct groups based on growth pattern: warm-season annuals and perennials, and cool-season annuals and perennials. Perennial forage species are far more common in pastures than annuals due to the decreased inputs, equipment, and labor resulting from one planting or seeding yielding several years of production (Ball et al., 2015). For those producers attempting to sustain their cattle herds on forages with minimal supplemental feed inputs, a mixture of perennial and annual forages is often utilized. Other techniques such as over-seeding or co-seeding multiple forage species in the same pastures can

serve to improve forage distribution throughout the year, decreasing the need for supplemental feeds.

The southeastern U.S. is well suited to forage production. Large amounts of marginal land and a mild climate facilitate extensive, forage-based cow-calf and stocker industries (Allen et al., 1996; Adkins et al., 2012). Producers often rely on a perennial grass species to grow and maintain their cows and calves. In the lower South, perennial warm-season grasses, namely bermudagrass [*Cynodon dactylon* (L.) Pers.] and bahiagrass (*Paspalum notatum* Flügge) dominate pastures and hayfields. These perennial grass species are apt for cow-calf and stocker cattle production scenarios; however, their nutritional values are typically not adequate to support desirable rates of growth and intramuscular fat deposition during the finishing phase of beef cattle production (Schmidt et al., 2013).

Usually, forage-finished beef producers utilize cool-season forages to achieve adequate rates of growth during the finishing phase of beef production. Cool-season forages typically exhibit forage quality and nutritive values capable of supporting animal average daily gains in excess of 1 kg, adequate for finishing beef cattle (Schmidt et al., 2013; Ball et al., 2015). Unfortunately, cool-season forages are only productive during the fall, winter, and spring and forage-finished beef consumers desire fresh, high-quality beef products throughout the year. To meet this demand, warm-season forages that are capable of supporting animal body weight gains at, near, or in excess of 1 kg d⁻¹ throughout the summer months are needed (Schmidt et al., 2013).

Warm-season annual grasses, such as pearl millet [*Pennisetum glaucum* (L.) R. Br.], offer several benefits to Southeastern forage-based beef production systems. Warm-season annual grasses are characteristically rapid-growing, yielding large amounts of dry matter in short periods of time (Ball et al., 2015). Furthermore, they are typically greater in nutritive value than their perennial counterparts. In combination, these traits enable well-managed, warm-season annual grass pastures to support increased grazing animal performance and greater stocking rates when compared with the perennial, warm-season grass species (Schmidt et al., 2013).

Pearl Millet

Introduction

Pearl millet is a warm-season, annual grass native to northern Africa. It is widely used as a grain and forage crop, occupying more than 25 million hectares and can be grown throughout the U.S. (Burton and Powell, 1968; Sheahan, 2014). Pearl millet is a bunch grass that exhibits erect growth that will achieve heights of 1.2 to 2.4 m at full maturity but should be grazed or harvested in an immature growth stage, when sward height reaches approximately 60 cm (Fribourg, 1995; Kajuna, 2001). Plants are leafy and tolerant of drought, acidic soils, and low soil organic matter. Dry matter production of pearl millet has shown to be responsive to nitrogen fertilization (Fribourg, 1995). Pearl millet is typically lower yielding and slower growing than forage-type sorghums and sorghum hybrids (*Sorghum* spp.) but exhibits greater leaf:stem ratio and regrowth potential than sorghums due to prolific tillering (McLaughlin et al., 2004). Forage-type pearl millets are tolerant of defoliation; however, a stubble height of 15-20 cm is recommended to ensure regrowth and tillering from basal buds.

History of Pearl Millet

It is widely accepted that humans have cultivated pearl millet for several millennia (Manning et al., 2011). Cultivated and wild-type pearl millets have been identified in plant impressions from pottery artifacts dating from circa 4500 to 3000 years BP discovered in the southwestern portion of the Sahara Desert, in what is present day Mauritania (Amblard and Pernés, 1989). These impressions are likely the result of a tempering process relying on chaff and other harvest byproducts of pearl millet as a fuel source (Manning et al., 2011). Interestingly, Amblard and Vernet (1984) discovered rock engravings of bovines in the same archeological site and claim these are indicative of bovine breeding practices.

Breeding of Pearl Millet

Pearl millet was first seeded in the United States in 1860 but domestic breeding did not begin until 1936, nearly eight decades after its introduction (Gulia et al., 2007). India led breeding efforts for both grain- and fodder-producing pearl millet hybrids with efforts bolstered by the development of Tift 23A, a cytoplasmic male sterile (CMS) hybrid, by Glenn Burton during the late 1950s and 1960s (Burton 1958; 1965; Rai and Singh, 1987). These breeding efforts would vastly improve hybrid pearl millet production in India throughout the 1960s and later, in the U.S., Glenn Burton along with Wayne Hanna would go on to develop traits for dwarfism, early maturity and several other traits during the 1980s at the U.S. Department of Agriculture-Agricultural Research Service Research Center located in Tifton, GA (Andrews et al., 1993; Gulia et al., 2007). In the southeastern United States, marginal cropland, drought-

proneness, and high-incidence of pests and diseases continue to drive crop improvement of pearl millet.

Dwarf and semi-dwarf varieties of pearl millet have been developed with an emphasis on increasing leaf: stem ratio, digestibility, and rust resistance (Andrews and Kumar, 1992). Utilization of pearl millet as a grazed forage is difficult due to rapid growth rates over the relatively short growing season (McCartor and Rouquette, 1977). Nonetheless, pearl millet can augment warm-season forage production in grazing-based production systems, especially in scenarios when forage nutritive value is of great importance, such as beef forage-finishing systems (Fontaneli et al., 2001).

Management of Pearl Millet

Pearl millet should be seeded to a depth of 1 to 2.5 cm at a rate of 11 to 17 kg ha⁻¹ in the spring though early summer with grazing or cutting occurring approximately 40 d following seeding. Multiple, staggered seedings can be utilized if a grazing season longer than 90 d is desired. Pearl millet should be fertilized with phosphorous and potassium according to soil test recommendations and with nitrogen at seedling emergence and following the first cutting or approximately halfway through the grazing period. During drought conditions, care should be taken to avoid nitrate accumulation by timing nitrogen applications and rainfall events. This will ensure biomass production is great enough to balance nitrogen uptake, preventing nitrate poisoning in grazing animals.

Pearl millet is tolerant of drought and the high temperatures characteristic of the summer months in the southeastern U.S. making it a popular forage crop in the region. Negative effects

of moisture deficiency on the dry matter production of pearl millet were demonstrated by Rostamza et al. (2011). They report dry matter yields declined (19.5, 18.1, 14.0, and 10.0 Mg ha⁻¹) as irrigation initiation thresholds increased (40, 60, 80, and 100% depletion of available soil water, respectively). The authors cite reduced leaf: stem ratio as an indication of water deficiency in pearl millet plants and a contributor to the observed decline in dry matter yields. The same study reported percent total digestible nutrients (TDN) declined (54.70, 54.45, 53.15, and 51.41%) as irrigation initiation thresholds increased (40, 60, 80, and 100% depletion of available soil water, respectively). The observed reductions in TDN are attributable to increased (32.77, 32.99, 34.72, and 36.44%, respectively) percent of acid detergent fiber (ADF), a mostly indigestible fraction, as irrigation frequency declined. Rostamza et al. (2011) also reported percent crude protein (CP) increased (15.60, 15.94, 17.41, and 19.19%) with irrigation initiation thresholds (40, 60, 80, and 100% depletion of available soil water, respectively). This is likely an artifact of reduced dry matter yields and the tendency of pearl millet to accumulate nitrates during drought conditions.

'Tifleaf 3' Pearl Millet

The University of Georgia Coastal Plain Experiment Station and USDA-ARS released 'Tifleaf 3' pearl millet in April of 1995. It is a semi-dwarf, leafy, forage-type pearl millet produced via three-way hybridization between dwarf CMS single-cross F₁ hybrid Tift 8593 and a dwarf pollinator Tift 383. With regards to forage yields, uncut height, grazing animal performance, and *in vitro* dry matter digestibility (IVDMD) 'Tifleaf 3' is similar to 'Tifleaf 2', a predecessor cultivar. However, 'Tifleaf 3' exhibits improved resistance to rust (*Puccinia*

substriata), a problematic fungal pathogen of pearl millet, compared with ‘Tifleaf 2’ (Hanna et al., 1997; de Carvalho, et al., 2006).

Brown Mid-Rib Pearl Millet

‘Exceed’ brown mid-rib pearl millet is a dwarf variety of pearl millet containing the brown-mid-rib (BMR) genetic mutation. The BMR trait is a genetic mutation that phenotypically exhibits brown-colored vascular tissues in the leaf blade, sheath, and stem tissues of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) in addition to pearl millet. The first record of the BMR phenotype was reported nearly 90 years ago by Jorgenson (1931) in maize and was associated with reduced lignin content and altered lignin composition by Kuc and Nelson (1964). Despite its association with reductions in dry matter yields, the BMR mutation was chemically induced via diethyl sulfate or ethyl methane sulfate in sorghum and pearl millet due to the negative relationship between digestibility and lignin content (Porter et al., 1978; Cherney et al., 1988).

As of 2019, only three BMR mutants of pearl millet have been described, one arising from diethyl sulfate mutagenesis (Cherney et al., 1988) and the other two rising from spontaneous mutagenesis, one in a germplasm isolated in Zimbabwe (Gupta, 1995) and one in Tifton, GA (Degenhart et al., 1995). All three of these mutants are allomorphic, making the BMR mutation in pearl millet difficult to characterize; the affected enzyme has not been reported (Sattler et al., 2010; Christensen and Rasmussen, 2019). In pearl millet, the BMR trait has been associated with significant reductions in yield. Mustafa et al. (2004) found dry matter yield of BMR pearl millet was 42% lower than that of a wild-type pearl millet while reductions in acid

detergent lignin were only 25%. The same study also reports significant improvements in crude protein and dry matter degradability for BMR pearl millet compared with wild-type pearl millet. Akin et al. (1991) reported similar improvements in digestibility of the BMR mutant pearl millet but yield data was not provided. To date, no grazing trial has compared BMR and non-BMR pearl millet on the basis of an animal performance metric. Therefore, implications of the observed differences in forage nutritional value and production between BMR and non-BMR pearl millet on animal performance have yet to be elucidated in a grazed pasture scenario.

Due to its relative novelty and the availability of other BMR pearl millet varieties on the market, information on ‘Exceed’ BMR pearl millet is limited and nearly absent in scientific literature. The few exceptions are discussed herein. A variety trial conducted in Vermont found two-harvest average dry matter yields and nutritive values of ‘Exceed’ and ‘Tifleaf 3’ pearl millet to be similar (Darby et al., 2018). Another variety trial conducted in Knoxville, TN by the University of Tennessee Beef and Forage Center found ‘Exceed’ pearl millet yielded similar amounts of dry matter as ‘FSG 114’ BMR forage sorghum, the top yielding variety of warm-season annual grass in the trial (Bates et al., 2014). In a study examining the effects of including ‘Exceed’ BMR pearl millet into the diet of lactating dairy cows, Harper et al. (2018) reported a pearl millet silage-based total mixed ration (TMR) supported lesser milk yields than a corn silage-based TMR, although milk fat and lactose percentages and production were similar for both diets. These results can be attributed to increased starch concentration and the resultant increase in digestibility of the corn silage-based TMR compared with pearl millet silage-based TMR.

Issues with Pearl Millet

While pearl millet exhibits several favorable traits, there are some issues to be considered. The southeastern U.S. is characterized by a warm, humid climate that is well suited for pearl millet as well as a host of pests and pathogens. The chinch bug and false chinch bug [*Blissus leucopterus leucopterus* (Say) (Heteroptera: Blissidae) and *Nysius raphanus* Howard (Heteroptera: Lygaeidae), respectively] are common pests of warm-season grasses and pearl millet is a favored host (Ni et al., 2009). Management of these pests is imperative to prevent significant reductions in forage production and quality. Beta-cyfluthrin or zeta-cypermethrin can be applied 2 to 3 weeks after seedling emergence to prevent damage to the pearl millet crop. Subsequent applications should be made following cutting or grazing to protect regrowth.

Rust of pearl millet, arising from the fungal pathogen *Puccinia substrata*, is a major source of damage in pearl millet production. While rust resistance has been an impetus of pearl millet breeding efforts for decades, in humid, high-rainfall areas it remains a concern for producers. Infections, especially early, can result in significant decreases in dry matter yield, forage quality, and stand persistence. Risk of infection increases as ambient temperatures rise. Therefore, seeding of pearl millet should occur as early as possible to allow plants to become well-established prior to increased risk of infection (Wilson et al., 1996; de Carvalho et al., 2006). As use of fungicides are not recommended in forage production scenarios, care should be taken to select a rust-resistant variety of pearl millet.

Palatability of pearl millet can be depressed due to increased alkaloid concentrations arising from prolonged drought periods. Rouquette et al. (1980) reported drought stressed forage contained 180 to 460 mg kg⁻¹ DM total alkaloids and was not consumed by cattle while non-drought stressed stands of pearl millet contained 10 to 20 mg kg⁻¹ DM total alkaloids and was

readily consumed. Pearl millet is a drought-tolerant warm-season annual forage option, but intake may decline during drought conditions due to elevated alkaloid concentrations.

Forage Nutritive Value and Mass of Pearl Millet

Forage nutritive value refers to several chemical components of forages that are associated with animal performance metrics. These indices are commonly used to predict forage intake and digestibility and explain differences in animal performance. Acid and neutral detergent fiber fractions (ADF and NDF, respectively), lignin, and crude protein (CP) content of forages can be determined by chemical methods and or near infrared reflectance spectrometry (NIRS) that utilizes dual analyses to generate prediction equations based on correlations between chemical and spectral readings. These values can then be used to calculate dry matter intake (DMI), relative forage quality (RFQ), and total digestible nutrients (TDN).

Forage mass, as defined by Allen et al. (2011), is a measurement of the total dry weight of forage per unit area of land above a defined height at a specific time. While there are several ways to measure and report forage production, dry matter yield at a given time or over a given time period are the commonly used metrics.

Pearl millet has exhibited forage nutritive value greater than or comparable to other warm-season grass species in several previous grazing studies. Harmon et al. (2019) reported TDN of pearl millet was similar to BMR and non-BMR sorghum-sudangrass [*Sorghum bicolor* (L.) x *S. arundinaceum* (Desv.)] throughout the grazing season in two out of three years with values ranging from 550 to 604 g kg⁻¹ DM. The same study also reported RFQ of pearl millet was similar to or greater than BMR and non-BMR sorghum-sudangrass in those same two years

with values ranging from 112 to 139. However, the sampling method used by Harmon et al. (2019) did not sample whole plants but rather the portions of the plants that the grazing animals were consuming, mainly leaf blades. Schmidt et al. (2013) found pearl millet was greater in CP and lesser in NDF and ADF (22.79, 49.83, and 22.89%, respectively) than bermudagrass (15.18, 65.48, and 27.96%, respectively). Schmidt et al. (2013) also reported pearl millet exhibited the greatest average forage mass of all the species in their study [alfalfa (*Medicago sativa* L.; 2,041.1 kg ha⁻¹), bermudagrass (1,501.1 kg ha⁻¹), chicory (*Cichorium intybus* L.; 1,829.8 kg ha⁻¹), cowpea (*Vigna unguiculata* L.; 1,542.3 kg ha⁻¹), and pearl millet (2,804.3 kg ha⁻¹)]; however, statistically significant differences in average forage mass were not found. In a study comparing several varieties of pearl millet and sorghum-sudangrass, Fontaneli et al. (2001) found CP and *in vitro* organic matter digestibility (IVOMD) of three varieties of pearl millet to be similar to or greater than two varieties of sorghum-sudangrass with values ranging from 134 to 160 g kg⁻¹ DM for CP and 662 to 695 g kg⁻¹ DM for IVOMD across two years. The same study reported total forage mass of 'Tifleaf 2' pearl millet was greater than or similar to both varieties of sorghum-sudangrass in 1996 (6.60, 6.11, and 7.44 Mg ha⁻¹, respectively). Machicek et al. (2019) compared the effects of three different harvesting regimes, thrice at 30-d intervals, twice at 45-d intervals, and once at 90-d of BMR sorghum-sudangrass and BMR pearl millet. They reported TDN of BMR-pearl millet was similar to or greater than TDN of BMR-sorghum-sudangrass within harvest regime in both 2016 and 2017. Pearl millet exhibited TDN values of 68.5, 67.4 and 60.4% at 30-, 60-, and 90-d harvest intervals, respectively, 66.0 and 62.6% at 45- and 90-d harvest intervals, respectively, and 59.9% at one 90-d harvest in 2016. In 2017, pearl millet exhibited TDN values of 63.5, 59.7, and 59.0% at 30-, 60-, and 90-d harvest intervals, respectively, 61.5 and 59.0% at 45- and 90-d harvest intervals, respectively, and 58.6% at one

90-d harvest (Machicek et al., 2019). Forage mass of BMR pearl millet and BMR sorghum sundangrass were found to be similar within harvesting regime with BMR pearl millet yielding a total of 3.96 and 6.00 Mg ha⁻¹ for 30-d intervals, 3.81 and 5.64 Mg ha⁻¹ for 45-d intervals, and 6.29 and 9.87 Mg ha⁻¹ for one 90-d interval in 2016 and 2017, respectively (Machicek et al., 2019). These data suggest pearl millet is greater in forage nutritive value and can yield more forage mass than bermudagrass and is similar to sorghum-sudangrass for both of these metrics. While measurements of forage nutritive value and mass are useful tools in the comparison of forages, animal performance and stocking rate are the ultimate assays of the utility of a forage in a grazing-based production system.

Animal Performance on Pearl Millet

Previous studies examining pearl millet in grazing trials have reported a vast range in animal performance. Schmidt et al. (2013) reported average daily gains (ADG) of only 0.56 kg while Duckett et al. (2013) reported ADG of 1.61 kg of steers grazing pearl millet. McCartor and Rouquette (1977) found pearl millet supported steer ADG ranging from 0.27 to 1.01 kg; Harmon et al. (2020) reported an intermediate ADG value of 0.85 kg. The nutritive value of pearl millet is greatest during the immature growth stages, declining as maturity increases. Furthermore, Fontaneli et al. (2001) suggested warm-season annual grasses are high in nutritive value only when harvested frequently as their rates of growth are rapid. This is further evidenced by the stocking rates needed to maintain a specified grazing pressure in pearl millet pastures which can fluctuate several fold over a 90-d grazing season (McCartor and Rouquette, 1977). This led McCartor and Rouquette (1977) to conclude consistent gains are difficult to maintain with pearl millet, which may explain the inconsistencies in ADG reported in the literature (Ball et al.,

2015). Nonetheless, McCartor and Rouquette (1977) posit pearl millet is capable of supporting ADG of 1 kg over a 90-d grazing season and this claim is supported by the results reported by Duckett et al. (2013).

Finishing Cattle on Pearl Millet

Using pearl millet in forage-finished beef research and systems is not a novel practice as several studies have examined the utility of pearl millet as a forage for growing and finishing beef cattle. Pearl millet has been compared with other cool- and warm-season forages as well as grain-based rations on the bases of forage production and nutritional value, animal performance, carcass characteristics, and meat quality attributes. The general outlines and the limitations of these studies are discussed below and presented topically.

Larick and Turner (1990) utilized intensively grazed pearl millet, sorghum-sudangrass, or fescue-clover mixed pastures for finishing beef heifers. Heifers grazed forages for 84 d and then were finished on a corn-based feedlot ration for 0, 54, or 82 d prior to slaughter. Larick and Turner (1990) report the effects of forage type on animal performance, carcass characteristics, sensory evaluations, and fatty acid data. However, comparisons of the effects of days on a grain-based diet are averaged for all forage types despite reporting effects of forage type on several variables.

Maruri and Larick (1992) examined the effects of finishing cattle on pearl millet, pearl millet with limited grain supplementation, each for 101 d prior to slaughter, or pearl millet for 101 d followed by 63 d in a feedlot with *ad libitum* access to a rolled oats-based total mixed ration. Animal performance was not reported by Maruri and Larick (1992) but they report and

discuss treatment effects on carcass characteristics and meat quality attributes with special attention to meat flavor.

Duckett et al. (2013) compared alfalfa, pearl millet, and mixed pastures containing several cool-season forages with a grain-based feedlot ration for finishing beef cattle. Steers only grazed the forage treatments for 40 d prior to slaughter. Therefore, the reported effects of forage type on animal performance, carcass characteristics, and meat quality may be limited.

Schmidt et al. (2013) compared alfalfa, bermudagrass, chicory, cowpea, and pearl millet for their utility in a forage-finished beef production system. Although Schmidt et al. (2013) reported forage mass and some aspects of forage nutritive value, in addition to carcass characteristics and meat quality attributes, much of the pertinent forage management-related data, such as forage allowance and stocking rate, is absent from the publication. Given the aforementioned effects of forage and grazing management on animal performance, particularly on warm-season annuals, these data are needed to elucidate the effects of forage type on other variables of interest.

The series of papers published by Harmon et al. (2019; 2020) and McKee et al. (2020) report on the most complete study examining warm-season annual grasses for forage-finished beef production to date. This study compared pearl millet, a mixture of pearl millet and crabgrass (*Digitaria sanguinalis* L.), sorghum-sudangrass, and BMR-sorghum sudangrass for their utility in a forage-finished beef production system. Forage-, animal-, and meat-related data are all reported in detail, allowing for the complex relationships governing these variables to be explored.

Carcass Characteristics and Meat Quality

Carcass characteristics of economic impact include: hot carcass weight (HCW), dressing percent (DP), carcass fatness as measured by back-fat thickness, marbling, and percent of kidney, pelvic, and heart fat, muscling as estimated by the area of the longissimus muscle, color of lean and fat, and maturity. Consumers have become accustomed to meat from carcasses that have an USDA Quality Grade of at least low-Choice and exhibit bright, cherry-red lean and white fat that are consistently achieved by the grain-finishing beef production paradigm (Martin and Rogers, 2004). Generally, forage-finished beef carcasses are lighter in weight, leaner, more mature, lower in dressing percentage, and exhibit yellower fat and darker lean than grain-finished beef carcasses (Bowling et al., 1977; Kerth et al., 2007; Scaglia et al., 2012; Duckett et al., 2013; Koch et al., 2018). These discrepancies are primarily due to the difference in nutritional density and content of forage- and grain-based diets, with a few exceptions. However, several studies have found the effects of these differences on carcass characteristics and meat quality can be minimized if forages of good quality are utilized, facilitating the production of carcasses of adequate weight, muscling, and fatness while not significantly increasing maturity (Muir et al., 1998; Martin and Rogers, 2004). The dietary effects on meat quality and carcass characteristics as well as their underlying mechanisms are discussed below. Additionally, the findings of previous research examining the effects of finishing beef cattle on warm-season annual grasses, with an emphasis on pearl millet, on meat quality and carcass characteristics are also discussed.

Carcass Characteristics

Cattle are typically fed to a target weight or back fat thickness. The factors determining these benchmarks are largely economical but can also be influenced by cattle genetics. Because a majority of forage-finished beef is not marketed through traditional routes, timing of slaughter of forage-finished beef cattle is typically determined by animal weight or age with forage availability playing a major role in determining the value of these variables.

Plane of nutrition significantly influences carcass weight, fatness, muscling, and dressing percentage. Because forage-based diets are typically lesser in caloric density than grain-based diets, forage-finished cattle grow slower and begin to deposit fat later than their grain-fed counterparts (Martin and Rogers, 2004). If animal age at slaughter is controlled for, these differences can be more pronounced. However, Nour et al. (1994) claimed if uniform cattle are finished to a consistent grade endpoint on forages or grain, differences in carcass composition resulting from nutritional discrepancies are less distinct. This claim was confirmed by the findings of Mandell et al. (1997) who reported carcasses of cattle finished to 4, 7, or 10 mm of back fat thickness on roughages or a corn-based ration exhibited similar carcass characteristics, excluding longissimus muscle area, regardless of diet. Nevertheless, forage-finished cattle typically take longer to achieve a certain weight or thickness of back fat and therefore may be older at slaughter and thus, yield more mature carcasses than grain-finished cattle (Shackelford et al., 1995). Producers looking to increase carcass weight and fatness by increasing the length of the finishing period, whether grain- or forage-finishing, may increase cost of production and likelihood of negative effects of carcass maturity on other carcass characteristics and meat quality attributes.

Hot Carcass Weight and Dressing Percent

Hot carcass weight (HCW), sometimes reported simply as carcass weight, is taken once the slaughter process has been completed and prior to carcass washing and chilling. Typically, a heavier animal will yield a heavier carcass although several factors can influence this ratio, typically reported as dressing percent (DP). Carcasses achieving HCW of greater than 410 kg (900 lbs.) or less than 272 kg (600 lbs.) may be discounted by meat packers due to several factors such as the desire for consistency in the beef industry (USDA-AMS, 2020). Larick and Turner (1990), Maruri and Larick (1992), Duckett et al. (2013) and Harmon et al. (2020) all reported HCW of animals finished on pearl millet to be less than 272 kg and did not differ from HCW of animals finished on other forages. Schmidt et al. (2013) is the only study that reported HCW of greater than 272 kg (302.3 kg) for pearl millet-finished carcasses. Duckett and Harmon reported HCW of steers finished on pearl millet was less than steers finished on bermudagrass, alfalfa, and cowpea. As previously mentioned, length of the finishing period and, resultantly, carcass characteristics of forage-finished beef are often determined by forage availability and growing season. This is particularly true in a research setting where protocols requiring finishing animals to a particular nutrition-dependent endpoint, be it fat thickness or weight, are not practical due to the risk of exhausting forage resources prior to achieving targeted endpoints.

Dressing percent is calculated by dividing the hot carcass weight by the live weight of an individual animal and multiplying by 100. As the blood, head, hide, organs, and viscera are removed during the conversion of a beef animal to a beef carcass, the weights of each of these fractions effect hot carcass weight and dressing percent. Differences in dressing percentage of forage- and grain-finished beef carcasses can be largely attributed to the differences in bulk

density and passage rate of the diets. Because forage-based diets are typically more voluminous and require longer fermentation times in the rumen than grain-based diets, forage-finished cattle often have larger, heavier rumens (Beacom, 1984; Minick et al., 2001). When combined with diet-related effects on carcass fatness and muscling, a depression of dressing percentages of forage-finished beef carcasses is often observed (Fluharty et al., 2009). Dressing percentages of beef carcasses from animals finished on pearl millet have shown to be similar to those of beef carcasses of animals finished on chicory and bermudagrass (Schmidt et al., 2013), pearl millet and crabgrass and BMR and non-BMR sorghum-sudangrass (Harmon et al., 2020), and alfalfa (Duckett et al., 2013).

Carcass Muscling

Carcass muscling is typically reported as rib-eye area or longissimus muscle (LM) area and is used in the calculation of USDA yield grade, an indicator of the yield of closely trimmed, boneless, retail cuts from a carcass (Hale et al., 2013). Longissimus muscle area is taken at the interface of the 12th and 13th ribs and is positively correlated with carcass weight, dressing percent, and plane of nutrition (Pariacote et al., 1998). Carcasses of forage-finished beef animals typically exhibit a LM area that is less than grain-finished beef carcasses largely due to nutritional differences of the two production systems (Larick et al., 1987). Nevertheless, pearl millet-finished beef carcasses have shown to have LM area similar to that of grain-finished beef carcasses (Maruri and Larick, 1992). Other studies report LM area of pearl-millet finished beef carcasses to be similar to that of other forages but less than that of grain-finished beef carcasses (Duckett et al., 2013, Schmidt et al., 2013; Harmon et al., 2020).

Carcass Maturity

Carcass maturity is used rather than chronological age at slaughter because exact age is typically not known. Furthermore, carcass maturity is influenced by several variables other than animal age at slaughter and has been shown to be correlated with several factors influencing meat quality. Maturity is determined by assessing both lean and skeletal maturities of a carcass. Typically, skeletal maturity is ascertained from the degree of ossification in the cartilage and bone characteristics from the sacral to thoracic regions of the vertebral column while lean maturity is based on color, texture, and firmness of the longissimus muscle at the interface of the 12th and 13th ribs (Hale et al., 2013).

Increased maturity of forage-finished beef carcasses can also be associated with activity level. Forage-finished beef production systems typically utilize grazing instead of direct feeding of preserved forages or green chop. Grazing typically results in increased activity compared to eating from a trough in a feedlot setting, resulting in increased use of muscles. Muscle use is positively correlated with myoglobin content, the primary pigment influencing meat color. This results in darker, more mature looking meat (Vestergaard et al., 2000). This is evidenced by Srinivasan et al. (1998) who reported heme iron, myoglobin, and total iron content was greater in forage-fed than grain-fed animals which they attributed to increased muscle use via grazing activity.

Skeletal maturity typically exhibits a strong, positive correlation with lean maturity and these two variables are used to calculate overall carcass maturity (Hale et al., 2013). Skeletal maturity is determined by assessing the degree of ossification of the cartilage connecting sacral,

thoracic, and lumbar vertebrae as well as the cartilage on the dorsal side of these vertebrae and the spinous processes. The shape and appearance of the rib bones can also be used to determine the skeletal maturity of a beef carcasses. As an animal ages the cartilage will become more rigid via ossification and rib bones will flatten, widen, and become whiter in color as they lose their ability to produce red blood cells (Fluharty et al., 2009).

Carcass maturity has been negatively associated with palatability and it contributes to the determination of USDA quality grades, a major determinant in carcass valuation (Berry et al., 1974; Hale et al., 2013). As animals age, their muscles become coarser via increases in fiber diameter and the amount of collagen crosslinks, decreasing tenderness (Tuma et al., 1962). Also, increased myoglobin content has been associated with several undesirable off-flavors, namely livery flavors (Yancey et al., 2006). Pearl millet-finished beef carcasses were reported to be of similar maturity to beef carcasses finished on other warm-season annual grasses by Harmon et al. (2020). Other studies that examined pearl millet-finished beef carcasses did not report carcass maturity.

Carcass Fatness

Carcass fatness plays an important role in determining USDA yield grade, an indicator of yield of boneless, closely trimmed retail cuts from a carcass. Carcass fatness also contributes to assessing USDA quality grade via intramuscular fat or marbling. Carcass fatness can be measured in several ways; however, back-fat thickness (FT) and percent of kidney-pelvic-heart (KPH) fat are the most commonly used. Fat thickness and KPH fat are used along with hot carcass weight and longissimus muscle area to calculate USDA yield grade (Hale et al., 2013).

Of these three metrics of carcass fatness, marbling score and FT are the most important as they have direct effects on palatability and tenderness, in addition to carcass value. Kidney-pelvic-heart fat is used as an estimate of internal fat of the carcass and is positively correlated with overall carcass fatness. The relationships between carcass fatness and palatability and tenderness are discussed in the section entitled “Meat Quality”.

Amount of intramuscular fat or marbling has been positively correlated with beef tenderness, juiciness, flavor, and overall palatability (Savell et al., 1987; Lorenzen et al., 1999, 2003; O’Quinn et al., 2012). As a result, marbling scores contribute significantly to carcass value via their impact on the determination of USDA quality grades. Back-fat thickness is a measurement of the thickness of the subcutaneous adipose tissue at a defined location on the carcass, typically at the interface of the 12th and 13th ribs (Hale et al., 2013). It is often used as an indicator of the amount of finish or overall fatness of a carcass and it is positively correlated with marbling (Tatum et al., 1982). However, this relationship may be weaker in forage-finished beef carcasses than grain-finished beef carcasses due to discrepancies in metabolism and lipogenesis arising from differences in nutritional content of forage- and grain-based finishing diets.

Intramuscular fat deposition in cattle is dependent upon consumption of excess net energy and which is typically achieved by feeding grains during the finishing period (Park et al., 2018). Acetate, arising from the fermentation of forage in the rumen, is the primary substrate of *de novo* fatty acid synthesis in ruminants. Diets rich in grain, that is, rich in starch, also produce significant amounts of propionate when fermented in the rumen. As a result, starch-rich diets have a much lower acetate: propionate ratio (A: P) than forage-based diets. This difference in A: P produced by the fermentation of different diets has shown to effect deposition of intramuscular

fat in cattle; reduced A: P shows a positive correlation with amount of intramuscular fat (Smith et al., 2018). Propionate is absorbed by the animal and can be converted into glucose in the liver via gluconeogenesis. Glucose can also be absorbed in the small intestine of cattle when diets rich in starch are fed (Ørskov, 1986). Glucose has shown to be a metabolic precursor to intramuscular fat deposition (Smith and Crouse, 1984). While the amount of excess energy in the diet is the primary factor affecting the amount of fat deposition, reduced A: P of forage-based diets may result in a weaker relationship between intramuscular and subcutaneous fat deposition.

Carcasses of cattle finished on warm-season forages of good quality, such as pearl millet, have achieved marbling scores of slight, corresponding to USDA Select quality grade (Maruri and Larick, 1992; Schaake et al., 1993; Duckett et al., 2013; Schmidt et al., 2013; Harmon et al., 2020). Larick and Turner (1990) reported heifers finished on pearl millet for 84 d exhibited marbling scores of small, corresponding to the lower third of USDA Choice quality grade. These data indicate cattle finished on pearl millet are capable of yielding carcasses with slight to small marbling scores, which is within consumer acceptability limits for marbling (Savell et al., 1987). Larick and Turner (1990) reported back-fat thickness of 1.29 cm and 2.5% KPH fat for 248-kg carcasses of heifers finished on pearl millet, both greater than that of sorghum-sudangrass- and tall fescue-clover-finished carcasses. These results were not consistent with those reported by Maruri and Larick (1992) who found carcasses of steers finished on pearl millet only had 0.5 cm of back-fat and 0.97% KPH fat but were similar in weight at 244 kg. This discrepancy might be a demonstration of the effect of sex class on fat deposition in beef animals (Berg et al., 1979).

Carcass Color

As previously mentioned, forage-finished beef carcasses typically exhibit darker lean and more yellow fat color than grain-finished beef carcasses. The importance of meat appearance to consumers is paramount to all other meat quality attributes (Mancini, 2009). Consumers have become accustomed to beef that exhibits bright, cherry-red lean and white fat and associate yellow fat and dark lean with old or diseased cattle and meat that is not fresh or wholesome (Dikeman, 1990). Observations of more yellow fat on carcasses from forage-finished animals has been attributed to increased beta-carotenoid content of forage-based diets (Yang et al., 1992). Meanwhile, several mechanisms have been proposed as the causative agents of darker lean color of forage-finished beef. Increased ultimate postmortem pH of muscle tissue due to reduced concentrations of glycogen in muscles at slaughter of animals finished on forages has been suggested as one of these mechanisms. While ultimate muscle pH does have a significant impact on meat color and overall appearance, plane of nutrition has little to no effect on ultimate muscle pH, given animals are not stressed prior to slaughter (Warner et al., 1986). Long term stress prior to slaughter has shown to reduce muscle glycogen content and, subsequently, increase muscle pH. Bowling et al. (1977) suggested the darker appearance of forage-finished beef could be attributable to increased stress prior to slaughter resulting from animals' lack of familiarity with people, confinement facilities, and handling. This, however, is not likely to be an issue in cattle that were finished on intensively managed forages due to the nature of this management practice. Several studies examining both the lean color and ultimate muscle pH of grain- and forage-finished beef have found no difference in either (Bidner et al., 1981, 1986; Morris et al., 1997). Amount of intramuscular fat may contribute to the improved appearance of grain-finished beef because it is lighter in color and therefore reflects more light than muscle tissue, giving well-marbled meat a brighter appearance (Craig et al., 1959). The most likely cause of darker lean

color exhibited forage-finished beef is increased levels of myoglobin resulting from increased activity, via grazing, as reported by Shorthose and Harris (1991) and Varnam and Sutherland (1995).

Duckett et al. (2013) reported that carcasses from cattle finished on alfalfa or pearl millet did not differ on the basis of lean or fat color. Harmon et al. (2020) reported no difference between beef carcasses from animals finished on pearl millet, BMR and non-BMR sorghum-sudangrass, or a mixture of pearl millet and crabgrass for subjective and objective fat and lean color. Schmidt et al. (2013) found pearl millet-finished beef carcasses exhibited similar lean and fat color to alfalfa-, bermudagrass-, and chicory-finished beef carcasses. These results indicate both lean and fat color of pearl millet-finished beef carcasses are similar to those from animals finished on other warm-season forages.

Introduction to Meat Quality

Meat quality includes to several traits associated with palatability and nutritional value of meat. These include both organoleptic traits such as tenderness, flavor, juiciness, appearance, smell, and firmness and also chemical traits such as lean: fat ratio and nutritional content. The relative importance of these meat quality characteristics is dependent on association with perceived value and consumer satisfaction. Research on meat quality of forage- and grain-finished beef has reported both similarities and differences between the products of these two production systems.

Meat Tenderness

Over the past several decades, tenderness was considered by consumers to be the most important component of meat quality and determinate of acceptability (Dikeman, 1990; Koohmaraie, 1992; Miller et al., 1995; Brewer and Novakofski, 2008). Meat tenderness is dependent on two main elements, a muscle or myofibrillar component and a connective tissue or collagen component (Muir et al., 1998). Both elements of meat tenderness are influenced by ante- and post-mortem factors. Ante-mortem factors that can influence meat tenderness include breed, animal maturity, muscle location and use, sex class, and those associated with plane of nutrition. Post-mortem factors affecting meat tenderness are mainly impingements on the post-mortem activity of proteinases and interventions designed to improve tenderness via physical disruption of the myofibrillar structure such as electrical stimulation, blade tenderization, and grinding (Koohmaraie et al., 1995). Post-mortem proteolysis is more important in determining meat tenderness than connective tissue content and cross-linking in ante-mortem muscle (Koohmaraie, 1992). Diet-related effects on post-mortem proteolysis and connective tissues are discussed below.

Largely dependent on plane of nutrition, rate of growth prior to slaughter shows a positive correlation with meat tenderness. This relationship can be attributed to several mechanisms. Rapid growth rate is coupled with an increased rate of protein turnover in antemortem muscle. As a result, concentrations of proteolytic enzymes, namely the calcium-dependent enzymes called calpains, are increased in postmortem muscles. This increase in proteolytic enzymes results in increased post-mortem proteolysis and thus, more tender meat (Aberle et al., 1981; Fishell et al., 1985). Furthermore, Shackelford et al. (1994) reported a

negative relationship between live animal gain and postmortem activity of calpastatin, a calpain inhibitor.

Animal growth rate also exhibits a negative relationship with collagen stabilization via crosslinking, and resultantly, meat toughness (Aberle et al., 1981; Miller et al., 1983; Fishell et al., 1985). This appears to be both a direct and indirect relationship. While the direct relationship hinges upon increased amounts of soluble collagen resulting from a rapid growth rate, its ultimate effect on meat tenderness is up for debate (Etherington, 1987; Weston et al., 2002). The results of Fishell et al. (1985) and Aberle et al. (1981) support this hypothesis. However, Hall and Hunt (1982) found no relationship between animal growth rate and collagen solubility and Crouse et al. (1985) report cattle that grew at a slower rate, resulting from a lower plane of nutrition, yielded meat that was more tender than meat from animals with elevated rates of growth.

An indirect relationship governing animal growth rate and collagen stabilization is dependent on animal age at slaughter. Animal growth rate is negatively correlated with animal age at slaughter as faster growth rates generally result in animals achieving target slaughter weights at younger ages. Because animal age and the amount of intermolecular collagen cross-linking exhibit a positive correlation and cross-linked collagen is more stable and resistant to solubilization by heating, meat tenderness decreases as animal age at slaughter increases (Goll et al., 1964; Shimokomaki et al., 1972; Shorthose and Harris, 1990; Avery et al., 1996). As a result, rate of growth has an indirect influence on meat tenderness via animal age at slaughter.

Although there is a vast difference in caloric density between forage- and grain-based diets for cattle, evidence shows if rate of growth and resultantly, age and weight at slaughter, are controlled for, effects of plane of nutrition on tenderness as well as other attributes of meat quality are minimized. For example, in a comparison of forage- and grain-finished beef, McIntyre and Ryan (1984) reported cattle grown at a similar rate on forage or grain prior to slaughter at similar weight and chronological age produced meat of similar tenderness, regardless of diet. Because of the importance of tenderness in determining consumer satisfaction, meat quality, and perceived value, forage-finished beef producers should strive to maintain their animals' growth rates at or above a level that ensures economical animal slaughter weights at slaughter ages comparable to those of commodity beef.

Carcass fatness has also been associated with meat tenderness (Merkel and Pearson, 1975; Miller et al., 1987). The main mechanism of this relationship is carcass chilling rate as evidenced by Lochner et al. (1980) who demonstrated larger, fatter carcasses cool at a slower rate than smaller, leaner carcasses. The prolonged chilling time inhibits cold shortening of the muscles and allows for increased postmortem proteolysis, resulting in an increase in tenderness.

Amount of intramuscular fat or marbling may also influence meat tenderness as fat requires less force to chew and cut through than muscle tissue. Because intramuscular fat is positively correlated with carcass fatness, the relationship between marbling and tenderness can be difficult to isolate and may not contribute significantly to tenderness (Shorthose and Harris, 1991). Furthermore, the 1998 National Beef Tenderness Survey found USDA quality grade exhibited little to no correlation with objective and subjective measurements of tenderness when

postmortem aging time was controlled for at 19 d for retail cuts and 32 d for foodservice cuts (Brooks et al., 2000).

Forage-finished beef may stand to benefit more than grain-fed beef from longer postmortem aging periods due to the discrepancies in animal growth rate, carcass fatness, and animal age at slaughter. Length of postmortem aging of beef has shown to be correlated with tenderness although this relationship varies among USDA quality grades. Bratcher et al. (2005) reported no statistical increase in objective tenderness measurements after a postmortem aging period of 7 d for steaks from carcasses that exhibited marbling scores of modest (Md^0) or greater, corresponding to the USDA quality grades Choice, Choice⁺, and Prime, while steaks from carcasses that exhibited marbling scores of slight, corresponding to USDA quality grade Select, increased in objective tenderness until 14 d postmortem. It should be noted that results of Bratcher et al. (2005) were achieved with steaks from muscles from the chuck and knuckle (IPMS 115 and IPMS 167, respectively; USDA, 2014). Because these muscles are used for locomotion they stand to benefit more, with regards to postmortem aging and the resulting increase in tenderness, perceived value and consumer satisfaction, than muscles used for support, such as those from the rib and short loin primal cuts (IMPS 124 and 173, respectively; (Bratcher et al., 2005; USDA, 2014). Gruber et al. (2006) found a majority of increases in objective tenderness occurred prior to 15 and 26 d of postmortem aging for beef steaks cut from the longissimus dorsi, a support muscle, of carcasses that achieved USDA quality grades Choice and Select, respectively.

Based on the results of these studies, interactions between postmortem aging period and USDA quality grade are present. Therefore, studies examining the effects of treatments that may

affect USDA quality grade should take these interactions into consideration when determining appropriate postmortem aging periods of samples prior to objective and subjective analyses of tenderness. Smith et al. (1978) suggested a postmortem aging period of 11 or more days to maximize the tenderness of most muscles of the chuck, rib, loin, and round primal cuts from carcasses that achieved the USDA quality grade of Choice. However, when determining a postmortem aging period for beef in a research setting, other factors should be taken into consideration, especially if other organoleptic traits are to be determined by a sensory panel. Epley (1992) reported beef flavor is fully developed at 11 d postmortem and tenderness does not improve after this time point. However, the same report gives average postmortem aging periods of 5 to 7 d and 14 to 21 d for retail and foodservice beef cuts, respectively. Because the consumer experience is the ultimate test of beef quality, these values are perhaps more useful in determining an appropriate postmortem aging period in order to accurately mimic the consumer experience in a research setting.

Previous studies examining the effect of finishing cattle on pearl millet on meat tenderness have used both subjective and objective measurements. Schmidt et al. (2013) reported objective tenderness increased for beef striploin steaks from steers finished on pearl millet out to 28 d postmortem. They also report no difference between the tenderness of beef striploin steaks from steers finished on pearl millet, bermudagrass, or chicory, all of which were less tender than steaks from steers finished on alfalfa and cowpea. Because no interactions of forage type and aging period were found, Schmidt et al. (2013) do not report Warner-Bratzler shear force (WBSF) values for individual days of postmortem aging and forage treatments.

Duckett et al. (2013) found steaks from the longissimus muscle (LM) of steers finished on pearl millet, mixed pastures consisting of cool-season forages, alfalfa, or a grain-based concentrate exhibited similar objective and subjective tenderness scores at 14 and 28 d of postmortem aging despite observing treatment differences in carcass fatness, marbling score, and average daily gain. The similarities in tenderness reported by Duckett et al. (2013) are likely attributable to the minimization of confounding variables of animal age by the use of steers from contemporary calving groups and equal time on treatment across all treatments within year.

McKee et al. (unpublished data) reported no differences in objective or subjective tenderness for beef striploin steaks from steers finished on pearl millet, BMR sorghum-sudangrass, non-BMR sorghum-sudangrass, or a mixed pasture containing pearl millet and crabgrass. This study also utilized uniform time on treatment and animal age at slaughter within year to minimize confounding effects of animal age on meat tenderness. From these data it can be concluded that beef from steers finished on pearl millet are similar in tenderness to beef from steers finished on other warm-season grasses and grain-based diets when differences in animal age at slaughter and time on treatment are minimized.

Meat Flavor

Along with tenderness, meat flavor is of utmost importance to consumers (Martin and Rogers, 2004). Meat flavor is comprised of both its taste and aroma, as perceived by the taste buds and olfactory sense organs, respectively. Meat flavor can also be influenced by texture and juiciness but for clarity these organoleptic traits are discussed separately. Several ante- and postmortem factors influence beef flavor. These include diet, breed, and animal age at slaughter,

and length of postmortem aging, and preparation method, respectively (Elmore and Mottram, 2009). A majority of the flavors associated with meat are achieved through heating as raw meat exhibits only a metallic, blood-like taste (Mottram, 1998). Therefore, studies examining the flavor of meat utilize various cookery methods in the preparation of samples (AMSA, 2016).

Diet-related effects on meat flavor are not as pronounced in beef as they are in pork due to differences in digestive systems of the two species (Wood et al., 2003). However, studies comparing the flavor of meat from forage- and grain-finished cattle have found distinct differences and a majority of these differences arise from flavor of the fat (Maruri and Larick, 1992; Griebenow et al., 1996). Volatile lipid compounds contained in fat are largely responsible for fat flavor as evidenced by the strong correlation between fat flavor and fatty acid profile (Hornstein and Crowe, 1964; Melton et al., 1990; Van Elswyk and McNeill, 2014). Because carcass fatness and animal age at slaughter can influence the fatty acid profile of beef, studies comparing the flavor of forage- and grain-finished beef are often confounded with these two variables, particularly carcass fatness (Hidiroglou et al., 1987; Melton 1983). A review by Muir et al. (1998) reported 8 out of 12 studies reviewed found no difference between the flavor of meat from cattle finished on grain or forage when animals were slaughtered at the same weight and/or fatness. Melton (1983) suspected the lack of differences in forage- and grain-finished beef flavor reported in the literature were due to the inability of sensory panelists to detect certain flavor volatiles and the utilization of forages of good quality.

Despite inconsistencies in the literature, forage-finished beef is often associated with undesirable flavors that have been described as grassy, fishy, milky-oily, sour, and/or gamey (Berry et al., 1980; Melton et al., 1982; Larick and Turner, 1990). Larick et al. (1987) attributed

these off-flavors to the elevated concentrations of terpenoid compounds, particularly diterpenoids, in the fat of forage-finished beef. Diterpenoids are derived by ruminant microorganisms from phytol (3,7,11,14-tetramethyl-2-hexadecen-1-ol) found in chlorophyll. These findings were confirmed by Maruri and Larick (1992). However, Melton et al. (1982) reported a positive correlation between the intensity of off-flavors of forage-finished beef and the concentrations of omega-3 polyunsaturated fatty acids, namely C 18:3, in the meat. Other studies have also found elevated levels of omega-3 polyunsaturated fatty acids in forage finished-beef and have observed corresponding differences in sensory panel scores for off-flavor intensity (Duckett et al., 2007, 2009, 2013). Larick and Turner (1990) concluded that the relationship between sensory scores and fatty acid concentrations of forage- and grain-finished beef were more dependent on the phospholipid species that particular fatty acids were associated with than concentrations of fatty acids themselves. Martin and Rogers (2004) suggested increasing carcass fatness had a diluting effect on off-flavor-producing volatiles accreted in the fat and therefore animals that deposited more fat would be more palatable, regardless of diet type.

Increased levels of polyunsaturated fatty acids may also result in an increase in the development of undesirable, rancid flavors via lipid oxidation during postmortem aging, retail display, and cooking of forage-finished beef as unsaturated fatty acids are less resistant to oxidation than saturated fatty acids (Love and Pearson, 1971; Moore and Harbord, 1977; Yang et al., 2002). Although Gatellier et al. (2005) did not find this to be the case and Realini et al. (2004) only observed this relationship with ground beef but not in LM steaks. Forage-finished beef may be more resistant to oxidation due to increased levels of vitamin E, an antioxidant, when compared to grain-finished beef (Yang et al., 2002; Leheska et al., 2008).

Several studies have reported forage-finished beef to exhibit less beef-flavor intensity than grain-finished beef (Schroeder et al., 1980; Melton et al., 1982; Mandell et al., 1997; Kerth et al., 2007; Garmyn et al., 2010). This is likely an artifact of carcass fatness, particularly intramuscular fat, as Acheson et al. (2014) and Duckett et al. (2013) found a positive relationship between beef-flavor intensity and marbling scores. Nonetheless, as time on grain increases, concentrations of tetradecalactone and hexadecalactone in beef also increase along with intensity of desirable beef flavors, indicating a positive relationship between these chemicals and beef flavor intensity (Larick et al., 1987).

Previous studies examining the flavor of beef from cattle finished on pearl millet are limited. Duckett et al. (2013) found the pearl millet-finished beef exhibited lower beef-flavor intensity than alfalfa-finished beef but similar to mixed cool-season pasture-finished beef. The same study reports no effect of forage type on off-flavor intensity. McKee et al. (unpublished data) found beef- and off-flavor intensity to be similar for meat from steers finished on several warm-season annual grasses, including pearl millet. In both studies marbling score and polyunsaturated fatty acid content were also unaffected by forage treatment, which may explain these findings. These data suggest meat from cattle finished on pearl millet to be of similar beef- and off-flavor intensities of meat from cattle finished on other cool- and warm-season forages.

Juiciness

Juiciness is an organoleptic trait related to the amount of moisture released from meat during mastication as well as saliva produced during this process (Lawrie, 1974). A consumer survey conducted by O'Quinn et al. (2012) found juiciness ranked third in importance, behind

flavor and tenderness, of beef palatability traits. Nevertheless, Aberle et al. (2001) argued absence of juiciness negatively impacts other organoleptic traits and, as a result, consumer acceptability. This relationship can be explained by the interactions between several factors influencing meat palatability. Marbling is often believed to be a major determinant of meat juiciness. O'Quinn et al. (2012) reported juiciness decreased as intramuscular fat content decreased however, differences in juiciness were not significant between steaks from carcasses that graded low-Choice, Select, and Standard.

Effects of finishing system on beef juiciness have been shown to be minimal if slaughter weight or fat cover are controlled (Smith et al., 1977). Studies examining the juiciness of pearl millet-finished beef have reported that it did not differ from beef from animals finished on other forages or a grain-based ration or was greater than beef from animals finished on other warm-season grasses (Duckett et al., 2013; McKee et al., unpublished data). While slaughter weight and fat cover were dependent variables in these studies, these results indicate pearl millet-finished beef should exhibit an acceptable level of juiciness.

Proximate Analysis

Proximate analysis is used to determine chemical fractions of meat. These are typically moisture, protein, fat, and ash and are related to attributes of meat quality and carcass characteristics. Because marbling is typically determined subjectively, chemical determination of intramuscular fat percentage (IMF) is a useful, objective measurement to correlate with marbling score. Wilson et al. (1998) reported a strong correlation between USDA marbling score and IMF. Typically, as IMF increases, protein and moisture fractions will decrease as lean fractions of

meat are mostly water (FAO, 2007). Proximate analysis of forage- and grain-finished beef have found differences in IMF, moisture, and protein with grain-finished beef exhibiting more IMF than forage-finished beef. As a result, forage-finished beef is typically greater in protein and moisture than grain-finished beef. Schmidt et al. (2013) reported meat from steers finished on a variety of forages did not differ with respect to protein and fat content; however, moisture was greater for the pearl millet-finished beef than cowpea- and bermudagrass-finished beef. Duckett et al. (2013) found similar results and reported forage-finished beef was significantly leaner than grain-finished beef but differences in moisture and protein fractions were not significant. Harmon et al. (2020) reported no differences in moisture, protein, or fat content of beef from cattle finished on several warm-season grasses including pearl millet.

Ash of meat and meat products refers to the inorganic residue remaining after the combustion of the sample under atmospheric conditions. This fraction consists of minerals in the form of sulfates, silicates, oxides, and chlorides (Perez and Andujar, 1980). Ash content of beef is typically around 1% on a w/w basis (FAO, 2007). Previous studies have found the ash content of forage-finished beef to be of this magnitude (Leheska et al., 2008; Duckett et al., 2009; Harmon, 2017). These results indicate proximate analysis of pearl-millet finished beef to be similar to that of beef finished on other forages.

Soybean Hulls

Introduction

Soybean [*Glycine max* (L.) Merr.] hulls are a fibrous by-product of the soybean processing industry (Mansfield and Stern, 1994). They are largely fermentable in the rumen with

estimates of dry matter disappearance at 12 h as great as 65% (Hsu et al., 1987). Nutritionally, they are 12-14% crude protein and are balanced in calcium and phosphorus for supplementing beef cattle (0.63% and 0.23%, respectively; Kunkle et al., 2000).

Supplementation

Supplementation of animals on pasture has shown to improve animal performance and decrease the length of the finishing period while continuing to utilize forage resources (Hoveland and Anthony, 1977). Anderson et al. (1988) found soybean hulls to be similar to corn grain in improving performance of grazing animals and both pelleted and whole soybean hulls improved animal gains by 10% over forage alone. Pugh (2003) reported soybean hull supplementation at 1% BW d⁻¹ increased slaughter weights, longissimus muscle area, and back-fat thickness of cattle finished on cool-season forages. Supplementation of soybean hulls to grazing animals may also improve the digestibility of other fibrous feeds as Martin and Hibberd (1990) reported the digestibility of the acid detergent fiber fraction of poor-quality native grass hay increased as level of soybean hull supplementation increased up to 3 kg head⁻¹ d⁻¹. Pugh (2003) also reported improvements in overall diet digestibility via supplementation of soybean hulls at 0.70% BW d⁻¹ to cattle grazing tall fescue.

Carbon: Nitrogen Ratio

Improving carbon: nitrogen ratio in the rumen by supplementing energy in the form of a fibrous, by-product feed has shown to improve nitrogen use efficiency by the ruminant animal without depressing fiber utilization (Highfill et al., 1987; Richards et al., 2006). This may be useful with forages that are prone to nitrate accumulation such as pearl millet. Furthermore,

research suggests improvement in carbon: nitrogen ratio reduces the production of diterpenoids from chlorophyll by rumen microorganisms, possibly resulting in reductions of incidence and intensity of off-flavors of forage-finished beef (Griebenow et al., 1996). To date, no research has examined the efficacy of supplementation of soybean hulls to beef animals grazing pearl millet pastures on animal performance, carcass characteristics, and meat quality attributes.

Lipid Oxidation and Color Stability

Introduction

Several factors can influence the shelf-life of fresh beef; however, color is of utmost importance as appearance of meat is a main contributor to purchasing decisions of consumers (Carpenter et al., 2001). Consumers expect a beef product that exhibits a bright, cherry-red color and consequently, meat that is dark-red or brown in appearance is often discounted or removed from retail displays leading to economic loss (Suman and Joseph, 2013). Fresh beef cuts are typically packaged in oxygen-permeable plastic film and only have a shelf-life of two to four days due to development of metmyoglobin (Rikert et al., 1957a; 1957b). Myoglobin is the primary pigment in meat that is responsible for color. Its appearance is affected by its oxidation state with ferrous state oxymyoglobin exhibiting the bright, cherry-red color preferred by consumers. Once myoglobin has been oxidized to the ferric state forming metmyoglobin, it appears brown or dark-red and is thus associated with meat discoloration (Mancini and Hunt, 2005).

Meat Color

Forage-finished beef is often inherently darker in appearance and does not compete well at retail with grain-finished beef (Bowling et al., 1977). Crouse et al. (1984) found forage-finished steaks were darker than grain-finished steaks over 5 d of retail display and all steaks were “unacceptability dark in color” after 5 d of display. Reagan et al. (1977) reported forage-finished steaks exhibited greater discoloration and lesser consumer color and desirability scores than grain-finished steaks. Contrarily, Sapp et al. (1999) found forage-finished steaks retained greater objective redness values (C.I.E. a^*) than grain-finished steaks over 10 d of display in oxygen-permeable fresh meat film. The same study reported no difference in subjective color scores between grain- and forage-finished steaks over the 10-d display period. They concluded forage-finished beef production systems could yield a product with the same shelf-life color stability as grain-finished beef production systems. Similar results were reported by Gatellier et al. (2005). McKee et al. (unpublished data) found no effect of type of warm-season annual forage, including pearl millet, on objective color attributes of forage-finished beef over 7 d of simulated retail display. These results indicate pearl millet-finished beef to be similar to beef finished on other warm-season annual forages with respect to color stability.

Lipid Oxidation

Lipid oxidation is the process of lipid degradation and the formation of several reactive byproducts, namely aldehydes and ketones that are associated with rancid off-flavor and odors (Pearson et al., 1977). The reactive by-products of lipid oxidation have been shown to accelerate myoglobin oxidation, resulting in reduced color stability (Faustman et al., 1999). Because the

fatty acid profile of forage-finished beef typically contains elevated levels of polyunsaturated fatty acids that are less stable than saturated fatty acids, the reduced color stability of forage-finished beef reported in the literature may be due to increased rates of lipid oxidation (Aberle et al., 1981). However, effect of lipid oxidation by-products on color stability of forage-finished beef might be mitigated by leanness and α -tocopherol or vitamin E, an antioxidant, content of forage-finished beef products (Faustman et al., 1989; Daley et al., 2010). However, Yang et al. (2002) did not find any relationship between α -tocopherol supplementation and stability of lipids or color of forage-finished beef. Daley et al. (2010) suggested antioxidant enzyme content and activity is responsible for extension of shelf-life of forage finished beef. Descalzo et al. (2007) and Gatellier et al. (2004) reported glutathione, superoxide dismutase, and catalase activities and concentrations were greater in forage-finished beef than grain-finished beef.

Previous studies have reported lipid stability of forage-finished beef to be similar to or greater than grain-finished beef (Yang et al., 2002; Gatellier et al., 2005). McKee et al. (unpublished data) found no differences in lipid stability between meat from steers finished on pearl millet, a mixture of pearl millet and crabgrass, non-BMR sorghum-sudangrass, and BMR sorghum sudangrass. These results indicate pearl millet-finished beef exhibits similar lipid stability to beef from animal finished on other warm-season annual grasses and may be similar to lipid stability of grain-finished beef.

Heat Stress

The high ambient temperatures and relative humidity that characterize the Southeastern summer climate can negatively impact the welfare and performance of cattle. Heat stress occurs

when weather conditions, such as heat and humidity, overwhelm the normal processes an animal uses to dissipate heat (Summer et al., 2019). During heat stress events cattle exhibit several altered behaviors such as panting, excessive salivation, reduced dry matter intake, increased water consumption, and general malaise (Magrin et al., 2017; Marchesini et al., 2018). These activities result in a reduction in animal performance and efficiency via reduced dry matter intake and use of energy for thermal homeostasis rather than growth (St-Pierre et al., 2003). Carcasses and meat from beef animals slaughtered after a period of heat stress have exhibited reduced carcass weights, fat thickness, and darker, tougher meat (Mitlöhner et al., 2001; Marchesini et al., 2018). These issues may be more pronounced in animals consuming forage-based diets as roughages take longer to ferment in the rumen, increasing heat produced during rumination and potentially exacerbating a heat stress event. This may negatively impact animal performance, carcass characteristics, and meat quality of cattle finished on warm-season forages during the summer months in the southeastern U.S.

Conclusions

Pearl millet is a viable forage option for forage-finished beef production systems in the southeastern U.S., capable of supporting animal performance adequate to achieve carcasses and meat of acceptable quality. However, there is little to no literature comparing BMR pearl millet and pearl millet for use in a forage-finished beef production system. Furthermore, the effects of soybean hull supplementation to animals grazing pearl millet on animal performance, carcass characteristics, and meat quality have yet to be elucidated.

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CHAPTER 3

GRAZING EVALUATION OF PEARL MILLET WITH AND WITHOUT SOYBEAN HULL
SUPPLEMENTATION I: FORAGE PRODUCTION, FORAGE NUTRITIVE VALUE,
ANIMAL PERFORMANCE, AND CARCASS CHARACTERISTICS¹

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Abstract

A three-year grazing trial was conducted to evaluate pearl millet [*Pennisetum glaucum* (L.) R.Br. (PM)] and brown-midrib pearl millet (BMR) with and without supplementation of soybean [*Glycine max* (L.) Merr.] hulls (0.75% of body weight (BW); PM+S and BMR+S, respectively) in a forage-finished beef production system in the southeastern U.S. Sixteen 0.81-ha pastures were randomly assigned to one of four finishing treatments in a completely randomized, 2x2 factorial design. Each year, Angus-cross bred steers ($n = 32$; 3-yr average BW = 439 ± 75 kg) were randomly assigned to treatment and finished for 64, 90, and 84 d during the summers of 2016, 2017, and 2018, respectively. Forage nutritive value samples and estimates of forage mass were taken at initiation, termination, and every two weeks throughout the grazing trial. Average daily gain was calculated from fasted weights taken at grazing initiation and termination. Steers were harvested in September of each year and carcass data were collected 24 h postmortem. All data from 2016 was omitted due to a lack of pearl millet in the treatment pastures. All data were analyzed using PROC GLIMMIX in SAS v. 9.4. Botanical composition was unaffected ($P > 0.05$) by treatments with the exception of the initial sampling date of 2017 with PM and BMR pastures exhibiting greater ($P = 0.0330$) percentages of pearl millet than BMR+S pastures. Forage mass was similar ($P > 0.05$) across all treatments within harvest date and stocking rate was increased ($P = 0.0484$) by soybean hull supplementation during period 4 of 2017 for BMR+S only. Treatments did not affect ($P > 0.05$) total digestible nutrients or relative forage quality throughout the grazing seasons of 2017 and 2018. Supplementation improved ($P < 0.0001$) total average daily gain over forage alone which resulted in greater ($P < 0.0001$) final body weights across both years, but increases in pre-harvest live weights and hot carcass weights

due to supplementation were only observed in 2018 ($P < 0.0001$ and $P < 0.0001$, respectively). Darker subjective and objective lean colors for non-supplemented carcasses resulted in increased ($P = 0.0335$) lean maturity. Other carcass characteristics were unaffected ($P > 0.05$) by treatment. Results indicate that pearl millet is a viable warm-season forage option for forage-finished beef production systems and soybean hulls can improve animal performance with minimal impact on carcass characteristics.

Key Words: Forage-finished beef, pearl millet, soybean hulls, warm-season annual forages.

Introduction

American consumers are accustomed to high-quality, grain-finished beef. In the United States, grain-based feeding operations were readily adopted in the middle of the 20th century following a boom in corn production. Grain-finished beef has several advantages over beef from cattle finished on roughage-based diets. These advantages include increased meat quality, palatability, and consistency as well as a reduction in time needed to achieve economical slaughter weights (Hoveland and Anthony, 1977; Garmyn et al., 2010). Furthermore, finishing beef on grain-based rations reduces land use and associated costs while improving feed efficiency (Mathews Jr. and Johnson, 2013). Nonetheless, demand for forage-finished beef is increasing due to perceived health benefits and a general aversion to concentrated animal feeding operations (Duckett et al., 2009).

Consumers demand high-quality, fresh beef year-round. In order to meet this demand, forage-finished beef producers must utilize a host of forages to meet the nutritional requirements of their cattle throughout the year. During the summer months, animal performance typically declines due to reduced nutritive value of warm-season perennial grasses common in the southeastern U.S. (Hill et al., 1999). Warm-season annual grasses, such as pearl millet (*Pennisetum glaucum* L.R. Br.), are often greater in nutritive value than warm-season perennial grasses, can yield large amounts of dry matter, and exhibit favorable agronomic traits. Furthermore, pearl millet is well-adapted to the climate of the southeastern U.S. and is tolerant of drought and defoliation stresses (Bhattarai et al., 2019). As a result, pearl millet may offer beef producers a viable alternative to warm-season perennial grasses for beef production in the southeastern U.S.

Pearl millet is utilized as a forage crop in both grazed pasture and preserved forage production systems due to its large dry matter yields, ranging from 5.01 to 7.98 Mg ha⁻¹, in a relatively short period of time (Fontaneli et al., 2001). Previous research has shown pearl millet can support average daily gains in excess of 1 kg d⁻¹ and produce carcasses of acceptable muscling and marbling, particularly if grazed or harvested often (Larick and Turner, 1990; Fontaneli et al., 2001; Duckett et al., 2013). Furthermore, digestibility of pearl millet can be improved via reduction in lignin content by the incorporation of the brown-mid-rib (BMR) mutation (Akin et al., 1991; Mustafa et al., 2004). While Mustafa et al. (2004) reported BMR pearl millet exhibited 25% lower lignin content than wild-type pearl millet, a 42% reduction in dry matter (DM) yield was also observed, possibly negating improvements in digestibility in a grazing scenario where forage availability, intake, and animal performance share a positive relationship. To date, no information is available on BMR pearl millet in a grazed pasture scenario with regards to DM production, stand persistence, forage nutritive value, animal performance, and carcass characteristics.

Supplementation of beef cattle being finished on forages is a commonly used method to improve animal performance and decrease the length of the finishing period while continuing to utilize forage resources (Hoveland and Anthony, 1977). Soybean [*Glycine max* (L.) Merr.] hulls are a commonly available by-product feedstuff that is both palatable and rich in fiber. Anderson et al. (1988) reported soybean hull supplementation improved performance of grazing animals by 10%. Soybean hull supplementation at 1% BW d⁻¹ increased slaughter weights, longissimus muscle area, and back-fat thickness of cattle finished on cool-season forages (Pugh, 2003). Furthermore, Supplementation of soybean hulls to grazing animals may improve the digestibility

of other fibrous ingesta (Martin and Hibberd, 1990). Soybean hulls may improve animal performance and carcass characteristics in a pearl millet-based forage-finished beef production system without adding grain to the diet of cattle. However, the effects of soybean hulls as a supplement to beef animals grazing pearl millet has not been reported in the literature. The objectives of this study were to compare forage production, distribution, and nutritive value of pearl millet and BMR pearl millet in a forage-finished beef production system in the southeastern U.S. and establish the effects of forage variety and supplementation with soybean hulls on animal performance and carcass characteristics. We hypothesize pearl millet and BMR pearl millet are capable of supporting rates of animal growth near 1 kg d^{-1} over a 90-d grazing season. At this rate of growth, steers with approximate initial body weights of 450 kg should yield 300-350-kg carcasses of comparable quality to commodity beef. Furthermore, we expect supplementation with soybean hulls to increase animal performance over forage alone while increasing pasture stocking rates and improving carcass quality.

Materials and Methods

The experimental procedures were reviewed and approved by the University of Georgia Institutional Animal Care and Use Committee (Protocol #A2017 03-002-R2).

Weather Data

Precipitation, minimum ambient temperature, and maximum ambient temperature were measured and recorded daily by weather equipment located on the research site and operated by the University of Georgia College of Agricultural and Environmental Sciences Weather Network. Precipitation data was summed for all days in the respective month to calculate total

monthly cumulative precipitation. Maximum and minimum ambient temperatures were averaged by day and average daily temperatures were averaged by month to calculate the average monthly ambient temperature.

Forage Treatments and Management

A grazing trial was conducted during the summer months of 2016, 2017, and 2018 at the University of Georgia Department of Animal and Dairy Sciences Eatonton Beef Research Unit located near Eatonton, GA (33°24'08"N, 83°28'56"W). The soil series of the research site is described as Cecil sandy clay loam. Each year 16 0.81-ha pastures were randomly assigned to one of four treatments. The treatments included 'Tifleaf 3' pearl millet (PM; Southeast Agriseed, Rome, GA) and 'Exceed' brown-mid-rib pearl millet (BMR; Southeast Agriseed). Further, the paddocks in each forage type were randomly assigned to no supplementation or supplementation (+S) with pelletized soybean hulls at a rate of 0.75% of body weight (BW) d⁻¹. Pastures were seeded on 24 May, 26 April, and 2 May of 2016, 2017 and 2018, respectively, with a no-till drill (Haybuster 107; Duratech Industries International, Inc., Jamestown, ND) at a rate of 17 kg ha⁻¹ and depth of 2.5 cm with 18-cm row spacing approximately 7 d following an application of liquid glyphosate at 1.1 kg a.i. ha⁻¹ (Helosate Plus Advanced; Helm Agro US Inc., Tampa, FL). All pastures were fertilized with liquid nitrogen fertilizer at a rate of 56 kg ha⁻¹ (19-0-0, '19E'; R.W. Griffin, Attapulgus, GA) on 13 June, 18 May, and 31 May of 2016, 2017, and 2018, respectively, and at a rate of 34 kg ha⁻¹ on 6, 2, and 3 August of 2016, 2017, and 2018, respectively. All data from 2016 was excluded from the study due to poor establishment and lack of pearl millet in experimental pastures.

Animal and Stocking Management

Each year approximately 75 yearling Angus crossbred steers (*Bos taurus* L.) were received to the research site in February where they were backgrounded on annual ryegrass (*Lolium multiflorum* L.) forage and bermudagrass [*Cynodon dactylon* (L.) Pers.] hay in a nearby pasture. One week prior to the start of the grazing trial in each year, all steers were weighed following a 12-hr fast. Fasted weights were used to block the steers by body weight (BW) and 32 were selected in 2017 and 2018 (BW = 440 ± 60 kg and 451 ± 46 kg, respectively) for homogeneity in BW and calm demeanor. Steers were then paired to minimize variance in BW among pairs. Pairs of steers were then randomly assigned to treatment pastures.

All treatment steers were weighed at the initiation, approximate midpoint, and termination of the grazing period following a 12-h fast. Initial and final weights were used to calculate average daily gain (ADG) and total body weight gain (BWG). The grazing trial was initiated on 8 June and 13 June and terminated after 90 and 84 days of grazing on 7 and 5 September of 2017 and 2018, respectively.

All pastures were split into two 0.405-ha paddocks using temporary fencing and rotationally stocked with a stocking cycle of approximately 14 d. Length of stocking periods was determined based the optimal residual height for forage regrowth potential, approximately 20 cm, and visual estimations of forage mass (Allen et al., 2011). Steers not assigned to treatment and yearling heifers from the contemporary calving group on the research farm's herd were used as 'put-and-take' animals to maintain forage mass at a targeted value of $1000 \text{ kg DM ha}^{-1}$ with an additional animal added to each pasture for every $500 \text{ kg DM ha}^{-1}$ of forage mass as measured on

the rested paddock of each pasture. All animals were supplied with *ad libitum* access to shade, water and mineral (McNess Bova Breeder 6; Furst McNess Co., Cordele, GA; Table 3.1) while on trial. Pelletized soybean hulls were fed daily to supplemented treatment steers on an as is basis at a rate of 0.75% w/w of bodyweight d⁻¹. Pelletized soybean hulls were offered in black plastic troughs mounted to steel frames (3 m x 0.5 m x 0.25 m, approximately 0.5 m from ground level) to all animals in a pasture at 8:00 AM ± 2 h from the initiation of the grazing trial to 24 h prior to slaughter. Supplemented pastures were initially stocked with one additional animal per pasture in excess of the calculated stocking rate, determined by the methods described above, to account for the supplemental energy and protein provided by daily soybean hull supplementation. Soybean hulls were sampled twice each year for nutrient analysis to ensure minimal discrepancies in nutritional content between years (Table 3.2). Approximately 0.5-kg samples of soybean hulls were taken and placed in plastic bags at the initiation and termination of the grazing trial. These samples were then bulked within year and sent to the University of Georgia's Feed and Environmental Water Lab (Athens, GA) for determination of dry matter (DM), crude protein (CP), crude fiber, ash, and fat via wet chemistry and standard methods.

Pasture Sampling

Pasture botanical composition was estimated at the beginning, middle, and end of the grazing trial from the rested paddock of each pasture. Pasture botanical composition was estimated by clipping 0.093-m² quadrats to a height of 0.5 cm in three randomly selected locations per paddock. Botanical composition samples were then separated into pearl millet and non-pearl millet biomass, immediately weighed, and then placed into a 60°C forced air dryer to a constant weight. Dried botanical composition samples were then weighed for DM determination.

Forage mass was estimated at the initiation, termination and approximately every 14 d during the grazing trial for both rested and grazed paddocks. A power take-off-driven custom plot harvester attached to the three-point hitch of a tractor (University of Missouri, Columbia, MO) was used to cut three, randomly selected $4 \pm 1\text{-m}^2$ areas per paddock to a height of 10 cm. Total sample biomass was weighed immediately following harvest and a representative subsample from each sample was taken, immediately weighed, and then dried in a 60°C forced air dryer to a constant weight for DM determination.

Samples for the estimation of forage nutritional content were taken at the initiation, termination and approximately every 14 d during the grazing trial, on the same day pastures were sampled for forage mass estimation. Forage nutritional content samples were obtained by hand-grabbing forage material in a manner that imitated the grazing selections made by the cattle. Approximately 500 g of fresh forage was taken in this manner from the rested paddock of each pasture and fresh weights of these samples were taken immediately following sampling. Forage nutritional content samples were then dried to a constant weight in a forced air oven at 60°C . Samples were then ground to pass through a 2-mm screen in a Wiley mill (Thomas Scientific, Swedesboro, NJ). Ground forage nutritional content samples were then ground to pass through a 1-mm screen in a Cyclotec 1093 Sample Mill (Foss, Eden Prairie, MN). The samples were then sent to the University of Georgia's Feed and Environmental Water Lab (Athens, GA) for analysis. Determination of crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), and lignin was done by near-infrared (NIR) reflectance spectroscopy using a model 6500 (FOSS NIRS System, Inc., Laurel, Maryland) NIR analyzer. In reflectance mode, 5 g of homogenized samples were packed into ring cups and scanned from 400 to 2,498 nm to collect

spectra every 2 nm. The reflectance energy readings were referenced to corresponding readings from an internal ceramic disk. The recorded spectrum of each sample was the average of 32 successive scans. All spectral data were recorded as the logarithm of the reciprocal of reflectance ($\log 1/R$, R : reflectance). Acceptable instrument performance was confirmed through instrument response, photometric repeatability (noise) and wavelength accuracy tests, and check cell scan. Absorption of radiation in the region of 400 to 2,498 nm, the visible plus NIR region, was used to predict forage quality using the 2013 NIRS Consortium level 2 equation release statistics for grass hay (13GH50-2.eqa; NIRS Consortium, 2013). Predicted values for total digestible nutrients (TDN) and relative forage quality (RFQ) were then calculated.

Following termination of the grazing trial, treatment steers remained on treatment pastures for approximately one week prior to slaughter. When forage mass in the experimental pastures was deemed insufficient ($< 1000 \text{ kg DM ha}^{-1}$), baleage of the same forage species and variety as the assigned treatments was provided to the steers *ad libitum*. Annual pastureland utilized for silage was located near the research site, established, and fertilized in the same manner at the same time points as the experimental pastures. Silage pastures were clipped to a height of 18 cm during the boot growth stage and biomass was allowed to dry *in situ* to approximately 60% DM content. Forage was then baled (John Deere 569 Silage Special, Deere & Company, Moline, IL) into 1.25- x 1.25-m round bales that weighed approximately 500 kg. Cores from each bale were taken, bulked by forage variety and dried to a constant weight at 60°C in a forced air oven before being ground and analyzed in the same manner as samples for forage nutritional content. Forage bales were wrapped individually immediately following baling with

six layers of 1-mm silage wrap (Sunfilm, Tama USA Inc., Dubuque, IA) and allowed to ensile for a minimum of 40 d before being utilized (Table 3.3).

Slaughter, Live Weight, and Hot Carcass Weight

One day prior to slaughter, steers were transported 74 km from the research site to the University of Georgia Department of Animal and Dairy Science Meat Science and Technology Center (MSTC) located in Athens, GA. At the MSTC steers were held outside in covered pens, restricted from feed, and allowed *ad libitum* access to fresh water for 12 h antemortem. Steers were weighed immediately prior to slaughter. Steers were slaughtered under USDA inspection in two groups on 14 and 15 and 11 and 13 September of 2017 and 2018, respectively. Slaughter groups were balanced by treatment. Carcasses were split, weighed, washed, and sprayed with 2.5% lactic acid solution prior to being chilled at -2°C to an internal temperature of equal to or less than 4°C within 24 h postmortem. Split carcass weights were summed for each carcass and these weights were used as hot carcass weights (HCW).

Carcass Characteristics

Approximately 24 h postmortem, the right side of each carcass was ribbed between the 12th and 13th ribs and allowed to bloom for at least 30 min at 2°C before carcass data was collected. Back fat thickness (FT) was measured at the 12th and 13th rib interface, perpendicular to the outside of the carcass approximately three-quarters of the ribeye length from the chine-bone end. Back fat thickness was then adjusted (Adj. FT) based on total carcass fat cover to account for external fat removed with the hide during the harvest process and variability in carcass fat cover (AMSA, 2001). Degree of marbling, percent kidney-pelvic-heart fat (KPH),

skeletal and lean maturities and were also measured (AMSA, 2001; USDA-AMS, 2016). Degree of marbling data was converted to numerical values prior to analysis (e.g. practically devoid 0 – 99 = 100 – 199, traces 0 – 99 = 200 – 299, slight 0 – 99 = 300 – 399, small 0 – 99 = 400 – 499). Skeletal and lean maturity data were also converted to numerical values (e.g. A 0 – 99 = 100 – 199, B 0 – 99 = 200 – 299). Overall maturity and yield grade were then calculated for each carcass using standard methods (USDA-AMS, 2016). Lean texture and firmness of the longissimus muscle at the 12th and 13th rib were assessed for each carcass (1 = very fine, 2 = fine, 3 = slightly fine, 4 = slightly coarse, 5 = coarse and 1 = very firm, 2 = firm, 3 = slightly firm, 4 = slightly soft, 5 = soft, respectively). Objective lean color measurements were taken in a 50-mm diameter area, in triplicate, on the longissimus muscle at the interface of the 12th and 13th ribs with a Hunter-Lab Miniscan EZ (CR-310, Hunter Associates Laboratory, Inc., Reston, VA) illuminated at a 10° viewing angle, 2.54-cm aperture, and standardized to white and black tiles. Objective fat color measurements were taken in the same manner as objective lean color measurements on subcutaneous fat near the 12th and 13th ribs. Subjective lean and fat color values were assigned on the based on Japanese beef color standard tiles (1 = light cherry red, 2 = bright cherry red, 3 = cherry red, 4 = slightly dark red, 5 = moderately dark red, 6 = dark red, 7 = very dark red, 8 = extremely dark red and 1 = white, 2 = creamy white, 3 = slightly yellow, 4 = moderately yellow, 5 = yellow, respectively; Japanese Beef Lean and Fat Color Standards, The Japan Ham & Sausage Cooperative Association, Tokyo, Japan). For ribeye area the longissimus muscle at the interface of the 12th and 13th ribs were traced onto transparency film. Area of tracings was then measured using an USDA ribeye grid.

Statistical Analysis

Data from 2016 was not included the following analyses due to a lack of pearl millet in the treatment pastures during this year (Table 3.4). All data were analyzed using PROC GLIMMIX of SAS v. 9.4 (SAS Institute, Cary, NC). Means were separated using the LSMEANS statement with the PDIFF option. Statistical significance was set at $\alpha = 0.05$. *P*-values were adjusted for multiple comparisons using Tukey's HSD adjustment. For the analyses of treatment effects on botanical composition, forage nutritive value, and forage mass, pasture served as the experimental unit and was included as a random variable. These data were analyzed by sampling date and are presented by year because timing of sampling dates was confounded in year. For the analyses of stocking rate, pasture served as the experimental unit and was included as a random variable. These data were analyzed by grazing periods that corresponded to the sampling dates for forage nutritive value and mass and are therefore presented by year due to the confounding of timing of sampling dates in year.

For the analyses of treatment and year effects on initial, midpoint, and final BW, period 1, 2, and total ADG, total BWG, slaughter live weight, and carcass characteristics individual animal/carcass served as the experimental unit and data were analyzed across 2017 and 2018 with pasture included as a random variable. Treatment by year interactions were found for period 2, total ADG, total BWG, slaughter live weight, and hot carcass weight. Therefore, this data was further analyzed by year.

Results and Discussion

Weather Data

Total monthly precipitation (Figure 3.1) was equivalent to or in excess of the 100-year average during the observed months of 2017 and 2018 except for April of 2017 and August and September of 2018. In 2016 a period of limited rainfall following seeding of the treatment pastures in May resulted in sparse seed germination and was further exacerbated by competition of other grass species. Resultantly, experimental pastures in 2016 contained little to no pearl millet (Table 3.4). From the time of seeding of experimental pastures to termination of the grazing season the research site received precipitation on 62 and 58 days in 2017 and 2018, respectively, with precipitation equaling or exceeding 1 cm on only 26 and 15 of those days in 2017 and 2018, respectively. The average rainfall amount for days with rain from seeding of experimental pastures to termination of the grazing season was 0.95 and 0.81 cm in 2017 and 2018, respectively.

Average ambient monthly temperatures (Figure 3.2) were below or near the 100-year average during 2017 and 2018 except for April of 2017 and May and September of 2018. Negative impacts on animal performance related to heat stress were not measured in this study. However, weather conditions known to induce heat stress in cattle were observed during this study with maximum temperatures exceeding 32°C for 40 of 90 days in 2017 and 50 of 84 days in 2018.

Pasture Botanical Composition

Botanical composition is presented as percent of desired species by treatment within harvest date and year (Table 3.4). No differences were observed for botanical composition within year except for the initial harvest in 2017 where BMR+S pastures had lesser percent of pearl millet than PM+S and PM ($P = 0.0330$). Nearly pure stands of pearl millet were achieved for all treatments, excluding BMR+S, during 2017. This is likely attributable to establishment issues arising from weed competition in these pastures as BMR+S exhibited numerically lesser percentages of pearl millet at the middle and final harvests of 2017. Treatments were not expected to affect pasture botanical composition due to uniform management practices. Both varieties of pearl millet exhibited rapid and persistent growth throughout the grazing trial. Again, low soil moisture in 2016 delayed seeding and drought conditions following seeding resulted in poor pearl millet establishment and little to no pearl millet in the experimental pastures.

Forage Mass and Stocking Rate

No differences were observed for forage mass of rested paddocks of treatment pastures for any harvest date in 2017 or 2018 (Table 3.5). This is to be expected given the forages utilized in this study were of the same species and all pastures were under the same management strategy. Rested paddocks of all treatment pastures exhibited forage masses in excess of 1000 kg DM ha⁻¹ on every harvest date except for the PM and BMR pastures on the final harvest date of 2017. On said harvest date the forage mass of supplemented pastures were nearly double their non-supplemented counterparts; however, this difference was inadequate to elicit a treatment effect ($P = 0.3838$). Forage mass values reported by the present study are similar to or greater

than the range of values reported by Harmon et al. (2019) in a similar study who reported values ranging from 2,028 to 3,074 kg DM ha⁻¹ for pre-grazing forage mass of pearl millet over three grazing seasons during the summers of 2014, 2015, and 2016 at the same research site. Generally, forage mass was greatest at the 2nd, 3rd, and 4th harvest dates of both years, similar to the results reported by Harmon et al. (2019) and illustrative of the dry matter production curve of pearl millet (Ball et al., 2015).

Stocking rate (Table 3.6) was unaffected ($P > 0.05$) by treatments with the exception of the 4th grazing period of 2017 during which supplemented pastures of BMR pearl millet supported 1.2 more head ha⁻¹ than non-supplemented BMR pastures, respectively ($P = 0.0484$). The difference in stocking rate for this period corresponds to a numerical difference in forage mass between BMR+S and BMR pastures (2,504 kg DM ha⁻¹) on 26 July 2017. No other numerical differences of this magnitude were observed for forage mass throughout the 2017 and 2018 grazing seasons, contributing to the lack of treatment effects on stocking rate.

Stocking rate was expected to be increased by soybean hull supplementation due to the increased energy provided to the animals grazing supplemented pastures, thereby decreasing nutritional demands on the forage, decreasing grazing pressures, and increasing carrying capacities of supplemented pastures. However, estimates of forage mass indicate supplementation did not increase forage mass despite similar stocking rates across all treatments with the exception of the observed difference mentioned. These results are likely due to increased intake and digestibility of the forage arising from soybean hull supplementation as reported by Martin and Hibberd (1990).

Forage Nutritional Content and Value

Within harvest date, fiber fractions were largely unaffected by forage treatments (Table 3.7). However, on the first harvest date of 2017, BMR NDF content was greater than BMR than PM+S and BMR+S ($P = 0.0039$) with PM NDF being similar ($P > 0.05$) to all treatments. On the fifth harvest date of 2017, BMR+S exhibited greater ($P = 0.0062$) NDF content than PM and PM+S but did not differ ($P > 0.05$) from BMR which was similar ($P > 0.05$) to PM+S. No differences ($P > 0.05$) were observed for NDF content within harvest date in 2018. Values for NDF content in the present study were similar to the value of 49.83% reported by Schmidt et al. (2013) and the range of 50.3 to 64.5% reported by Harmon et al. (2019). Similar results were observed for ADF content of treatment forages. During the first harvest date of 2017, BMR ADF content was greater ($P = 0.0126$) than BMR+S but similar ($P > 0.05$) to PM and PM+S. No differences ($P > 0.05$) were observed for ADF content within harvest dates in 2018. Schmidt et al. (2013) reported pearl millet exhibited ADF content of 22.89%, similar to the findings of the present study only on the first sampling date of 2017. The range of ADF content observed during present study is comparable to the findings of Harmon et al. (2019) who reported pearl millet contained 27.2 to 36.9% ADF throughout a summer grazing season. Lignin content was also unaffected ($P > 0.05$) by treatments with the exception of the second harvest date in 2018 when PM and PM+S exhibited greater ($P = 0.0320$) lignin content than BMR and BMR+S. Although differences in lignin content of brown-mid-rib and wild-type pearl millet are well demonstrated in the literature (Akin et al., 1991; Mustafa et al., 2004), a general lack of differences in lignin content of appreciable magnitude in the present study are likely due to the sampling method. In an attempt to explain any potential differences due to forage variety in variables associated with

plane of nutrition, the samples for forage nutritive value in the present study were collected in a manner that was designed to mimic the grazing behavior of the treatment steers. As the treatment steers rarely consumed the stem fractions of the pearl millet plants, stem materials were seldom included in the forage nutritive value samples. Akin et al. (1991) demonstrated differences in lignin content between brown-mid-rib and wild-type pearl millet were greatest in the stem fraction. Therefore, the forage nutritive value samples of the present study were collected in a manner ill-suited to finding differences in lignin content of the treatment forages. Using a similar sampling method, Harmon et al. (2019) found non-BMR sorghum-sudangrass [*Sorghum bicolor* (L.) x *S. arundinaceum* (Desv.)] contained similar or lesser amounts of lignin than BMR sorghum-sudangrass throughout a 3-year grazing trial.

Treatment main effects on CP, TDN, and RFQ are presented in Table 3.8. Crude protein was unaffected ($P > 0.05$) by treatments within harvest date and year with the exception of the fifth harvest date in 2017. Samples collected on the fifth harvest date (17 August) of 2017 showed that PM CP was greater ($P = 0.0046$) than BMR and BMR+S and similar ($P > 0.05$) to PM+S. Crude protein content of BMR and BMR+S did not differ ($P > 0.05$) and PM+S and BMR were also similar ($P > 0.05$) at this time point. Similar to the present study, Schmidt et al. (2013) reported crude protein content of 22.79% for pearl millet, although only one value is given for the entire grazing season, limiting comparisons of CP content over the grazing season. Crude protein content of all treatments was greater than 16% on every harvest date throughout both 2017 and 2018 and thus was not a limiting factor for animal performance (NRC, 2000; Gleghorn et al., 2004). No differences were observed in TDN or RFQ within harvest dates across both 2017 and 2018. Total digestible nutrients and RFQ values reported by the present study are

similar to those reported by Harmon et al. (2019) for pearl millet. Treatment differences in forage nutritive value were not expected in this study due to the use of the same forage species and consistent management strategies across all treatments.

Animal Performance

Treatment and year main effects and treatment by year interactions for BW, total BWG, and ADG are presented in Table 3.9. There was not a year effect ($P > 0.09$) for any of the animal performance traits measured. This was expected given the consistencies in animal and forage management across years. Steers in all treatments had similar ($P = 0.9532$) average initial BW. Body weight of supplemented steers trended greater ($P = 0.0591$) than non-supplemented steers at the midpoint of the grazing trial; however, observed increases in animal performance due to supplementation would not result in increased BW until the termination of the grazing trial. Final BW of PM+S and BMR+S treatment steers was greater ($P < 0.0001$) than non-supplemented steers. This result is further explained by BWG and ADG data. Body weight gain was calculated as the total amount of gain from initial to final weights. Overall treatment differences for BWG showed that supplemented steers gained more weight than non-supplemented steers ($P < 0.0001$), but there was a treatment by year interaction ($P = 0.0141$; Table 3.10). In 2017 both PM+S and BMR+S gained more weight than PM ($P < 0.0012$), but BMR gains were not different ($P > 0.05$) from PM and BMR+S. In 2018 both groups of supplemented steers gained more weight than non-supplemented steers ($P < 0.0001$). Treatment effects on BW and BWG can be better explained by treatment effects on ADG.

As expected, supplementation with pelletized soybean hulls increased ($P = 0.0017$) ADG of treatment steers on pastures seeded with 'Tifleaf 3' pearl millet (PM and PM+S) by nearly 46% during period 1. Average daily gains exhibited by the BMR, BMR+S, and PM+S treatment steers did not differ ($P < 0.05$) during period 1. A treatment by year interaction ($P = 0.0429$) was observed for period 2 ADG (Table 3.10). Supplementation increased ($P < 0.0001$) ADG of PM+S and BMR+S treatment steers during period 2 of 2017 by 0.43 and 0.50 kg d⁻¹ or 87 and 128%, respectively. However, during period 2 of 2018, PM+S treatment steers gained 1.04 kg d⁻¹, more than triple that of PM treatment steers that only gained 0.32 kg d⁻¹. Supplementation increased ADG of BMR treatment steers from 0.17 to 1.10 kg d⁻¹, a 547% improvement ($P < 0.0001$). These values are much greater than the 10% improvement in performance of grazing animals due to supplementation with soybean hulls as reported by Anderson et al. (1988). Depressed gains of non-supplemented treatment steers during period 2 of 2018 are puzzling given forage availability and nutritive value were of adequate levels to support greater animal gains (NRC, 2000). Examination of ADG of individual PM and BMR treatment steers reveals 8 of 16 animals gained little or no weight (0 to 0.30 kg d⁻¹), and one that lost weight (-0.37 kg d⁻¹), during period 2 of 2018 despite all gaining in excess of 0.50 kg d⁻¹ during period 1 of the same year. A series of papers (Harmon et al. 2019; 2020) reported forage nutritive value and mass of pearl millet to be similar to the findings of the present study but ADG of steers finished on pearl millet to be 0.85 kg d⁻¹ in the second half of the grazing season. This suggests depressed forage intake of PM and BMR treatment steers during period 2; however, forage intake was not quantified in the present study. Examination of precipitation data from August of 2018 shows reduced rainfall amounts compared with August of 2017 and the 100-yr average for the month of August. However, the observed value of 6.63 cm of total precipitation for August of 2018 is

likely not low enough to elicit palatability-reducing increases in alkaloid concentrations of pearl millet in response to drought stress as reported by Rouquette et al. (1980). Increased animal performance due to supplementation with pelletized soybean hulls was expected given the additional energy provided by soybean hulls. However, during period 2 of 2018, improvements of the magnitude observed for ADG due to supplementation were not expected and poor performance of non-supplemented animals cannot be corroborated by corresponding data.

A treatment by year interaction ($P = 0.0058$; Table 3.10) was observed for total ADG, likely an artefact of the treatment by year interaction observed for period 2 ADG as previously discussed. During 2017 total ADG for PM+S and BMR+S treatment steers were similar ($P > 0.05$) respectively, and total ADG for BMR+S treatment steers did not differ ($P > 0.05$) from BMR which was similar ($P > 0.05$) to PM. Treatments did affect total ADG in 2017 ($P = 0.0012$) with supplementation increasing ADG of PM+S and BMR+S treatment steers by approximately 74 and 61%, respectively, over PM treatment steers. In 2018 total ADG for supplemented treatment steers was greater ($P < 0.0001$) than non-supplemented treatment steers with improvements in ADG of 0.51 and 0.65 kg d⁻¹ for PM+S and BMR+S, respectively.

Total ADG values for PM and BMR treatment steers in the present study are similar to the 0.56 kg d⁻¹ reported by Schmidt et al. (2013) but lesser than values of 0.85 kg d⁻¹ as reported by Harmon et al. (2020). Supplemented and non-supplemented treatment steers did not achieve the 1.61 kg d⁻¹ ADG reported by Duckett et al. (2013) over a 40-d finishing period for steers grazing pearl millet. Duckett et al. (2013) do not report forage nutritive value or weather data so this discrepancy cannot be explained via nutritional nor environmental differences. Furthermore, compensatory gain is unlikely to be responsible for the discrepancy between the ADG values

reported by Duckett et al (2013) and the present study due to the level of ADG, 0.91 kg d⁻¹, reported by Duckett et al. (2013) during the 92 day backgrounding period on mixed pastures prior to the pearl millet finishing period; although pearl millet finished steers were approximately 100 kg less in BW at initiation of the finishing period in Duckett et al. (2013) than the steers used in the present study.

Live Weight, Hot Carcass Weight, and Carcass Characteristics

There was a treatment by year interaction for slaughter live weight (LW) and HCW ($P = 0.0162$ and 0.0166 , respectively; Table 3.11 and Table 3.12). Both slaughter LW and HCW were not different among treatments in 2017 ($P = 0.7683$ and $P = 0.5655$, respectively), but in 2018 supplemented steers and carcasses were heavier ($P = 0.0001$) than non-supplemented steers and carcasses. In both years, PM and BMR carcasses were slightly heavier than those reported by Duckett et al. (2013) and Harmon et al. (2020) for steers finished on pearl millet (261 and 267 kg, respectively).

Treatment had no effect on DP, REA, FT, Adj. FT, or calculated yield grade ($P = 0.1521$, $P = 0.1698$, $P = 0.2308$, $P = 0.4532$, and $P = 0.7133$, respectively). Carcasses of steers finished on BMR+S exhibited greater ($P = 0.0470$) KPH than of those finished on PM, which was similar ($P > 0.05$) to BMR and PM+S. However, this did not affect ($P = 0.7133$) the calculated yield grade values due to the small magnitude of effect KPH has in the yield grade equation (USDA-AMS, 2016). Yield grades for all treatments in the present study ranged from 2.21 to 2.46, greater than the values of 1.89 and 2.16 reported by Harmon et al. (2020) and Schmidt et al. (2013), respectively. These differences can be attributed to discrepancies in the metrics used to

calculate yield grade observed in Schmidt et al. (2013), Harmon et al. (2020), and the present study.

Dressing percent, KPH, Adj. FT, and yield grade were all affected by year ($P = 0.0028$, $P < 0.0001$, $P = 0.0340$, and $P = 0.0036$, respectively). In 2017 carcasses exhibited greater dressing percent, KPH, and Adj. FT that resulted in increased yield grade compared with carcasses in 2018. Dressing percentages in the present study were around 60%, slightly greater, with the exception of PM, than the values of 58.92% reported by Schmidt et al. (2013) and greater than the values of 55.0 and 57.8% reported by Duckett et al. (2013) and Harmon et al. (2020), respectively. Dressing percentages observed in the present study were lower than the industry average for commodity, grain-finished beef which are typically around 63.5% (USDA-AMS, 2020). This is due, in part, to increased weight of the digestive tract of forage-finished animals resulting from increased gut fill at slaughter and decreased bulk density of forages relative to concentrate feeds (Bailey, 1984).

Back fat thicknesses of carcasses in the present study were greater than those reported by Maruri and Larick (1992), Duckett et al. (2013), Schmidt et al. (2013), and Harmon et al. (2020) for pearl millet-finished carcasses (0.50, 0.598, 0.45, and 0.50 cm, respectively). Carcass weights reported by Maruri and Larick (1992), Duckett et al. (2013), and Harmon et al. (2020) were lighter in weight at 244, 261, and 267 kg, respectively, which may explain the discrepancies in fat thickness. However, Schmidt et al. (2013) reported hot carcass weight of 302 kg for pearl millet finished steers, a similar value to those reported in the present study. Only PM+S and BMR+S treatment carcasses achieved adjusted back fat thicknesses greater than 0.76, a benchmark targeted for the prevention of increased toughness due to cold shortening.

Differences in REA were expected given the observed differences in HCW and a lack of differences in other yield- and maturity-related metrics. However, while numerical differences were observed for REA, with PM+S and BMR+S exhibiting larger REA than their non-supplemented counterparts, these differences were not statistically different ($P = 0.1698$). Duckett et al. (2013) and Harmon et al. (2020) both reported REA of 66.5 and 71.5 cm² for pearl millet-finished beef carcasses, respectively, less than the values reported in the present study, which ranged from 74.6 to 81.2 cm² across all treatments. These differences are likely attributable to the differences in HCW between these studies discussed above and similarities between the REA and HCW reported by Schmidt et al. (2013) (77.29 cm² and 302.3 kg, respectively) and the present study.

There were no treatment by year interactions ($P > 0.07$) for carcass quality attributes (Table 3.13). Marbling score was unaffected ($P = 0.6289$) by treatments with values ranging from Slight 84 to Small 41, corresponding to USDA quality grades of high Select and low Choice, given carcasses were of A maturity (USDA-AMS, 2016). Marbling scores observed in the present study for both supplemented and non-supplemented carcasses are greater than those reported by Duckett et al. (2013), Schmidt et al. (2013) and Harmon et al. (2020) (Slight 73, 21, and 70, respectively). While forage-finished beef carcasses are typically not graded for USDA quality grade, it is a useful metric in determining consumer acceptability and perceived value of a fresh beef product. Retail beef steaks and roasts are typically of USDA Select or Choice quality grade, denoting to the consumer a degree of marbling that are associated with desirable organoleptic traits such as tenderness, juiciness, and beef flavor intensity. Therefore, the

finishing treatments examined in this study are capable of producing beef carcasses of acceptable quality with respect to marbling scores (Savell et al., 1987).

Carcasses of steers finished on PM+S exhibited more youthful lean than those of steers finished on PM ($P = 0.0335$) but this did not affect the calculated values for overall maturity ($P = 0.5400$). The animals in the present study were all harvested at around 20 months of age which resulted in all treatments being within A maturity, similar to the results of Harmon et al. (2020) for carcass of steers finished on several warm-season annual forages. Differences were observed for subjective lean color ($P = 0.0488$) and lightness (L^* ; $P = 0.0304$) with carcasses of steers finished on PM+S having brighter red and lighter lean color than those from steers finished on PM. Lean maturity of beef is determined by its color and texture. Since no treatment effect was observed for lean texture ($P = 0.6923$) and subjective lean color and lean L^* reflectance values were both affected by treatments, it can be concluded that the observed differences in lean maturity are due to lean color as the L^* values trended in the same direction as the subjective color scores. Duckett et al. (2013), Schmidt et al. (2013), and Harmon et al. (2020) all reported no difference in objective lean color of beef carcasses from steers finished on several species of forages, including pearl millet.

Both subjective and objective (L^* , a^* , and b^*) measurements of fat color were unaffected ($P > 0.05$) by treatments with all carcasses exhibiting creamy white to slightly yellow back fat at the interface of the 12th and 13th ribs. Increased ($P = 0.0008$) fat a^* values were observed for carcasses in 2018 compared with 2017 were likely an artifact of reduced adjusted fat thickness observed during 2018 ($P = 0.0340$), resulting in increased transparency and redness of back fat arising from the muscle underneath on some of the carcasses with less fat cover. While carcasses

in 2017 exhibited brighter ($P = 0.0058$) red lean color, greater ($P = 0.0399$) lean L^* values, indicating lighter colored lean, and finer ($P = 0.0073$) textured lean than carcasses in 2018, carcass lean maturity was greater ($P < 0.0001$) in 2017 than 2018. Skeletal maturity was also greater ($P < 0.0001$) in 2017 than 2018 resulting in increased ($P < 0.0001$) overall maturity for carcasses in 2017 compared with 2018. Increased Adj. FT observed in 2017 likely contributed to the observed differences in lean color as fat insulates the carcass during initial chilling, resulting in a greater and more rapid decline in intermuscular pH as lactate producing anaerobic biochemical processes in postmortem muscle are more active at greater temperatures (Savell et al., 2005) which typically results in lighter and brighter lean color. Delayed carcass chilling also results in increased postmortem proteolysis, improving meat texture which may explain the finer texture of carcasses in 2017 compared with 2018 (Juárez et al., 2011). Nonetheless, the increased maturity of carcasses in 2017 compared with 2018 cannot be explained by corroborating data as finer textured, brighter lean is typically associated with more youthful animals (Hale et al., 2013).

Conclusions

‘Tifleaf 3’ and ‘Exceed’ BMR pearl millet can both be used as a grazed forage in a forage-finished beef production system, with forage variety having little effect on forage mass and nutritive value as well as animal performance. Furthermore, supplementation of soybean hulls at a rate of 0.75% of BW d^{-1} improves animal performance over forage alone but did not increase stocking rate. Pearl millet- and BMR pearl millet-finished beef carcasses exhibit similar HCW, muscling, and fatness. While lean maturity and color were affected by variety of pearl millet, overall maturity was unaffected by finishing treatment. Supplementation with soybean

hulls increased LW and HCW of steers finished on PM but LW and HCW of steers finished on BMR was similar to that of supplemented steers. Carcass characteristics used in the determination of yield and quality grades are indicative of cutability of carcasses and palatability of meat. Although forage-finished beef carcasses are typically not graded in the beef industry, the carcasses examined in the present study achieved an average USDA yield grade of 2 and USDA quality grades at the Choice-Select interface, indicating economical yields of closely trimmed retail cuts and marbling and maturity scores similar to commodity beef available to consumers at retail and foodservice outlets.

Acknowledgements

This project was supported in part by the Georgia Agricultural Commodity Commission for Beef and the United States Department of Agriculture National Institute of Food and Agriculture, Agriculture and Food Research Initiative CARE program 2016-68008-25145.

Conflict of interest statement. None declared.

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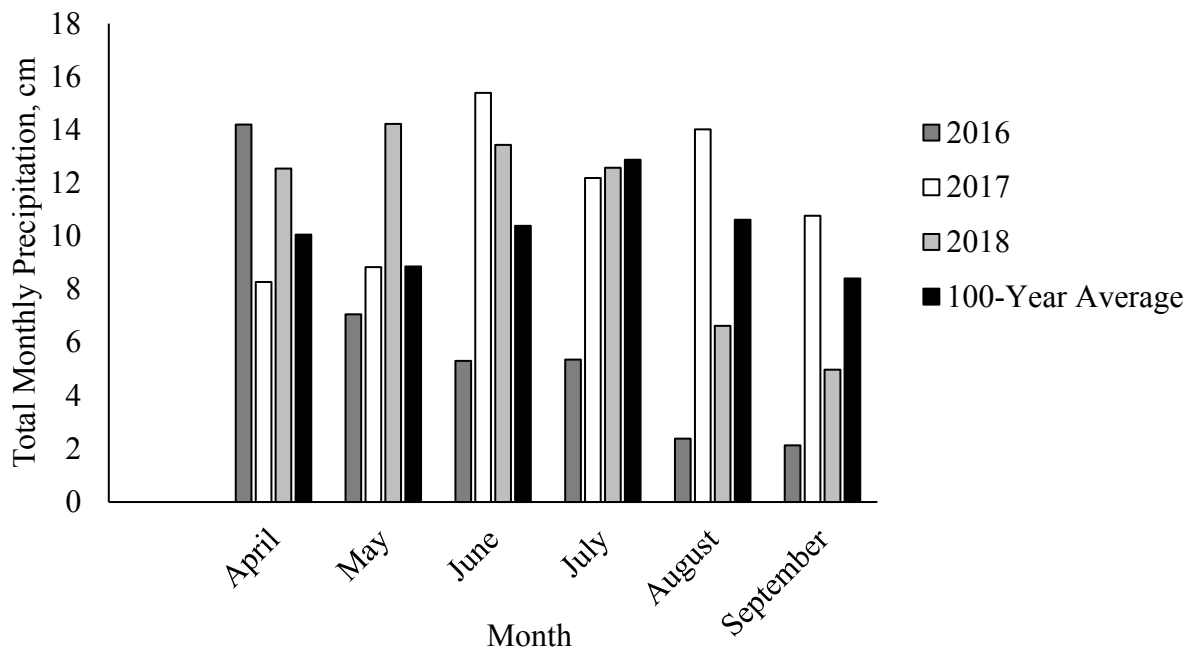


Figure 3.1. Cumulative monthly precipitation for April through September 2016, 2017, and 2018 and the 100-year average cumulative monthly precipitation April through September at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

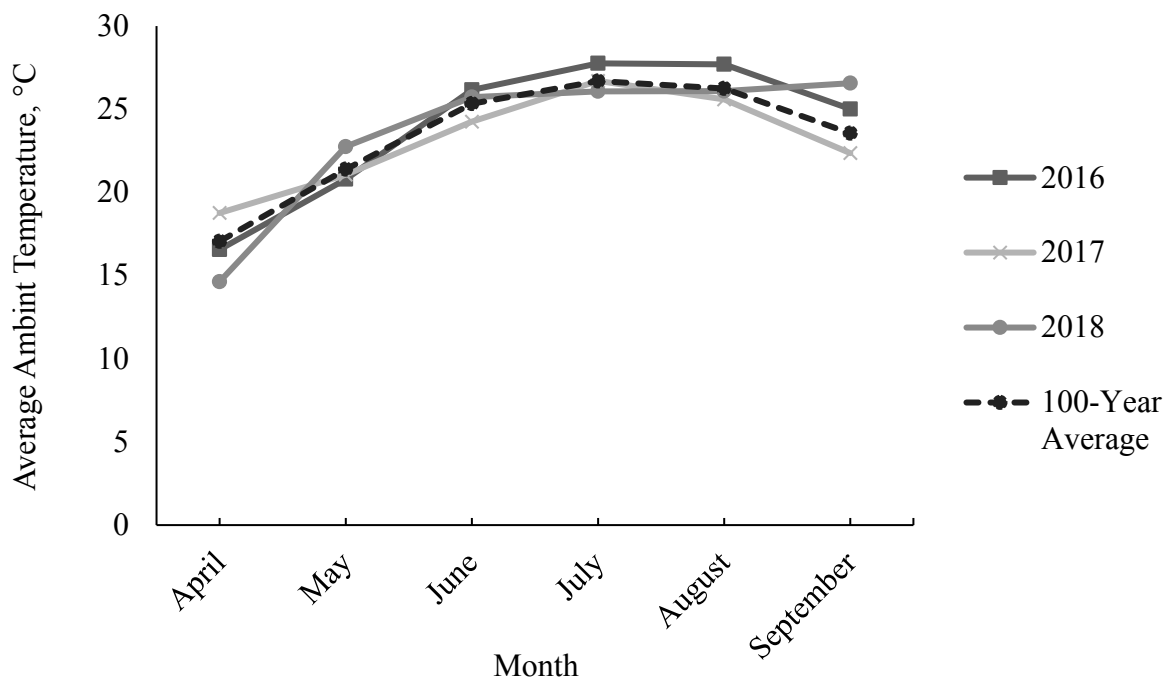


Figure 3.2. Average monthly ambient temperature for April through September of 2016, 2017, and 2018 and the 100-year average monthly ambient temperature for April through September at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Table 3.1. Composition of free choice mineral.¹

Ingredient	Guaranteed analysis
Calcium, %	13.2
Phosphorus, %	6.1
NaCl, %	20
Magnesium, mg/kg	2.6
Manganese, mg/kg	6,500
Zinc, mg/kg	9,000
Copper, mg/kg	3,000
Iodine, mg/kg	184.5
Cobalt, mg/kg	45
Selenium, mg/kg	39
Vitamin A, IU/kg	66,387
Vitamin D-3, IU/kg	66,139
Vitamin E, IU/kg	1,322

¹McNess Bova Breeder 6 (Furst McNess Co., Cordele, GA).

Table 3.2. Nutritional content of pelletized soybean hulls fed to steers grazing ‘Tifleaf 3’ pearl millet (PM+S) and ‘Exceed’ brown-midrib pearl millet BMR+S at a rate of 0.75% of body weight d⁻¹ during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Fraction, %	Year ¹	
	2017	2018
DM	87.4	87.2
CP	10.4	10.4
Crude Fiber	41.2	40.9
Ash	4.61	4.61
Fat	0.65	0.55

¹ 2016 data was excluded from the study due to poor establishment and lack of pearl millet in the experimental pastures (Table 3.4).

Table 3.3. Nutritional content as predicted by near infrared spectroscopy of pearl millet baleage harvested during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Year/Item, %	Forage Variety	
	PM ¹	BMR ²
2017		
CP	12.2	11.6
ADF	38.2	39.0
NDF	65.2	65.7
Lignin	5.34	5.82
TDN ³	56.3	53.6
RFQ ⁴	113	102
2018		
CP	7.32	9.71
ADF	44.5	40.8
NDF	71.2	66.8
Lignin	5.15	4.74
TDN ³	47.3	51.3
RFQ ⁴	70.5	90.4

¹ PM: 'Tifleaf 3' pearl millet.

² BMR: 'Exceed' brown mid-rib pearl millet.

³ TDN: Predicted total digestible nutrients = $(NFC \times 0.98) + (CP \times 0.87) + (FA \times 0.97 \times 2.25) + [NDFn \times (NDFDp \div 100)] - 10$ where CP = crude protein (% of DM), EE = ether extract (% of DM), FA = fatty acids (% of DM) = ether extract - 1, NDF = neutral detergent fiber (% of DM), NDFCP = neutral detergent fiber crude protein, NDFn = nitrogen-free NDF = NDF - NDFCP, also estimated as $NDFn = NDF \times 0.93$, NDFD = 48-hour in vitro NDF digestibility (% of NDF), NFC = nonfibrous carbohydrate (% of DM) = $100 - (NDFn + CP + EE + \text{ash})$, and $NDFDp = 22.7 + .664 \times NDFD$.

⁴ RFQ: Estimated relative forage quality = $DMI (\% \text{ of BW}) \times TDN (\% \text{ of DM}) / 1.23$.

⁵ 2016 data was excluded from the study due to poor establishment and lack of pearl millet in the experimental pastures (Table 3.4).

Table 3.4. Least squares means of treatment effects on botanical composition (pearl millet, % DM) in pastures seeded with pearl millet (PM) and brown mid-rib pearl millet (BMR) and supplemented with soybean hulls (PM+S and BMR+S, respectively) harvested at three dates in 2016, 2017, and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Year/Harvest	Treatment				SEM	P-Value
	PM	PM+S	BMR	BMR+S		
2016 ¹						
Initial	9.89	14.9	17.7	8.83	6.46	0.8645
Middle	24.6	14.7	14.8	10.2	6.39	0.7424
Final	15.2	8.18	11.7	12.0	6.80	0.9112
2017 ²						
Initial	88.6 ^a	85.0 ^{ab}	95.2 ^a	66.3 ^b	6.81	0.0330
Middle	91.9	85.3	100.0	70.4	10.1	0.2257
Final	93.8	100.0	83.3	63.9	11.3	0.1394
2018 ³						
Initial	61.2	55.5	57.4	52.8	12.21	0.9677
Middle	58.8	40.8	44.9	58.5	14.08	0.7308
Final	77.6	58.0	48.7	47.0	13.06	0.3412

^{ab} Means within a row without a common superscript differ ($P < 0.05$).

¹ Initial = 15 July; Middle = 16 August; Final = 14 September. Due to low establishment data from 2016 were not included in further analyses.

² Initial = 8 June; Middle = 26 July; Final = 7 September.

³ Initial = 13 June; Middle = 25 July; Final = 5 September.

Table 3.5. Least squares means of treatment effects on forage mass (kg DM ha⁻¹) in rested paddocks of pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and brown mid-rib pearl millet with soybean hull supplementation (BMR+S) pastures harvested at initiation of stocking periods during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Harvest Date	Treatment				SEM	<i>P</i> -Value
	PM	PM+S	BMR	BMR+S		
2017						
7 June	4,371	2,336	4,682	2,384	950	0.1764
26 June	5,173	6,514	5,030	4,968	995	0.6563
12 July	4,566	5,183	4,230	5,080	479	0.4654
26 July	3,555	4,494	2,980	5,484	695	0.0773
17 August	1,600	2,313	2,107	2,642	525	0.5644
29 August	966	1,540	822	1,528	365	0.3838
2018						
13 June	1,938	1,840	2,683	2,604	321	0.1543
3 July	6,510	5,624	6,174	6,107	516	0.6849
18 July	4,903	7,068	5,051	5,174	895	0.0699
31 July	4,481	4,067	4,573	3,968	564	0.8386
15 August	3,019	3,048	2,576	2,647	399	0.7687
29 August	2,474	2,318	2,206	2,093	390	0.9130

Table 3.6. Least squares means of treatment main effects on average stocking rates (head ha⁻¹) by period and year of pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and brown mid-rib pearl millet with soybean hull supplementation (BMR+S) pastures during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Grazing Period	Treatment				SEM	<i>P</i> -Value
	PM	PM+S	BMR	BMR+S		
Stocking Rate, head ha ⁻¹						
2017 ¹						
1	5.2	4.9	5.0	4.5	0.99	0.9158
2	4.7	5.2	4.5	5.3	0.45	0.2434
3	4.7	5.3	4.4	5.3	0.59	0.3239
4	3.7 ^{ab}	4.3 ^{ab}	3.5 ^b	4.7 ^a	0.43	0.0484
5	3.1	3.7	2.5	3.1	0.63	0.3096
6	3.1	3.1	3.1	3.1	0.03	0.0721
2018 ²						
1	3.6	4.2	4.1	4.8	0.54	0.2315
2	5.0	5.0	4.7	5.6	0.49	0.3298
3	5.0	5.0	4.7	5.6	0.49	0.3298
4	5.0	4.7	4.7	5.5	0.50	0.3110
5	4.5	4.0	4.2	4.0	0.54	0.6741
6	2.5	2.5	2.5	2.5	-	-

^{ab} Means within a row without a common superscript differ ($P < 0.05$).

¹ Period 1 = 6 June – 26 June, period 2 = 27 June – 12 July, period 3 = 13 July – 26 July, period 4 = 27 July – 17 August, period 5 = 18 August – 29 August, period 6 = 30 August – 6 September.

² Period 1 = 13 June – 3 July, period 2 = 4 July – 18 July, period 3 = 19 July – 31 July, period 4 = 1 August – 15 August, period 5 = 16 August – 29 August, period 6 = 30 August – 11 September.

³ 2016 data was excluded from the study due to poor establishment and lack of pearl millet in the experimental pastures (Table 3.4).

Table 3.7. Least squares means of treatment effects on neutral detergent fiber (NDF), acid detergent fiber (ADF), and lignin concentrations as estimated by near infrared spectroscopy of forage nutrient content samples harvested at initiation of stocking periods on rested paddocks of pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and brown mid-rib pearl millet with soybean hull supplementation (BMR+S) pastures during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Harvest Date	Treatment				SEM	P-Value
	PM	PM+S	BMR	BMR+S		
NDF, % of DM						
2017						
7 June	47.4 ^{ab}	45.0 ^b	47.9 ^a	44.1 ^b	0.50	0.0039
26 June	58.8	58.7	60.2	58.0	1.26	0.6831
12 July	58.0	58.5	56.5	58.7	2.39	0.9247
26 July	53.8	54.0	55.0	55.8	1.28	0.6509
17 August	54.6 ^c	54.8 ^{bc}	60.0 ^{ab}	60.7 ^a	1.25	0.0062
29 August	52.4	52.4	52.7	54.6	0.77	0.1725
2018						
13 June	50.9	50.4	53.1	54.4	1.80	0.4029
3 July	58.2	55.9	58.9	57.8	1.02	0.2549
18 July	60.4	57.9	60.6	60.3	1.22	0.3851
31 July	61.6	60.0	59.3	57.7	1.36	0.2915
15 August	58.8	56.4	58.30	58.1	1.45	0.6686
29 August	50.1	49.3	50.2	49.2	0.80	0.7700
ADF, % of DM						
2017						
7 June	23.9 ^{ab}	23.3 ^{ab}	24.3 ^a	22.4 ^b	0.35	0.0126
26 June	31.3	31.2	31.8	29.5	0.81	0.2526
12 July	30.8	31.6	29.8	31.0	1.73	0.8971
26 July	29.4	29.1	29.4	28.5	0.87	0.8710
17 August	31.8	32.3	35.1	34.9	1.11	0.1230
29 August	28.8	28.6	28.3	30.1	0.57	0.1581
2018						
13 June	27.1	26.7	28.3	28.3	0.95	0.5301
3 July	29.4	28.0	29.0	27.7	0.63	0.4474
18 July	31.3	29.8	31.0	31.0	0.71	0.5204
31 July	34.4	33.4	32.3	30.5	1.02	0.0932
15 August	33.1	30.7	31.2	32.4	0.94	0.3084
29 August	27.9	27.0	26.9	26.2	0.68	0.3813
Lignin, % of DM						
2017						
7 June	5.4	5.2	5.2	5.1	0.15	0.4766
26 June	5.7	5.7	5.2	5.2	0.16	0.0599
12 July	5.9	6.0	5.6	5.6	0.31	0.5756

26 July	5.3	5.5	5.5	5.2	0.20	0.7226
17 August	5.9	6.2	5.9	5.9	0.21	0.7177
29 August	5.4	5.4	5.0	5.2	0.14	0.2624
2018						
13 June	5.3	5.5	5.5	5.5	0.11	0.7874
3 July	5.3 ^a	5.3 ^a	4.9 ^b	4.9 ^b	0.12	0.0320
18 July	5.2	5.1	4.9	5.1	0.11	0.4696
31 July	6.5	6.0	5.6	5.9	0.30	0.2329
15 August	6.1	5.9	5.7	5.9	0.24	0.7036
29 August	5.5	5.1	5.1	5.1	0.13	0.1627

^{abc} Means within a row without a common superscript differ ($P < 0.05$).

Table 3.8. Least squares means of treatment effects on crude protein (CP), total digestible nutrients (TDN), and relative forage quality (RFQ) as estimated by near infrared spectroscopy of forage nutritive content samples harvested at initiation of stocking periods on rested paddocks of pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and brown mid-rib pearl millet with soybean hull supplementation (BMR+S) pastures during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Harvest Date	Treatment				SEM	P-Value
	PM	PM+S	BMR	BMR+S		
CP, % of DM						
2017						
7 June	26.3	26.1	26.6	27.8	0.55	0.2124
26 June	18.4	19.0	17.9	18.3	0.21	0.7952
12 July	18.3	18.5	17.6	18.0	1.71	0.9841
26 July	21.7	22.0	21.9	21.1	0.76	0.8613
17 August	22.2 ^a	21.8 ^{ab}	19.0 ^{bc}	18.2 ^c	0.73	0.0046
29 August	22.6	23.2	24.6	22.4	0.67	0.1398
2018						
13 June	25.5	25.4	22.8	23.3	1.42	0.4381
3 July	20.4	20.8	19.3	19.5	0.81	0.5305
18 July	18.7	19.4	17.1	18.0	1.26	0.6457
31 July	16.7	17.7	18.0	19.5	1.24	0.4904
15 August	18.2	19.1	18.2	19.2	1.11	0.8623
29 August	25.3	25.9	25.6	26.8	0.62	0.3946
TDN ¹ , % of DM						
2017						
7 June	70.0	65.0	64.0	66.0	0.53	0.0616
26 June	59.0	57.8	59.9	60.7	0.67	0.0507
12 July	58.2	57.5	58.7	57.8	1.31	0.9270
26 July	60.0	59.3	59.0	59.5	0.67	0.7478
17 August	55.8	56.2	52.1	53.6	1.10	0.0700
29 August	59.9	59.4	60.8	59.5	0.67	0.5057
2018						
13 June	63.6	62.9	68.0	61.9	0.75	0.3801
3 July	59.9	60.2	59.8	60.8	0.69	0.7497
18 July	58.5	58.5	59.7	59.2	0.61	0.4555
31 July	55.3	56.6	58.1	58.3	1.13	0.2656
15 August	56.8	58.7	58.2	58.1	0.84	0.4515
29 August	60.3	61.8	62.3	62.3	0.51	0.0521
RFQ ²						
2017						
7 June	158.6	163.9	158.5	169.0	2.85	0.0663
26 June	129.9	124.6	133.1	139.3	3.54	0.0724
12 July	127.5	122.4	130.6	125.7	6.72	0.8561

26 July	136.3	133.4	131.8	134.4	3.63	0.8468
17 August	115.9	117.0	97.4	102.9	5.52	0.0684
29 August	136.5	134.4	140.8	133.5	3.26	0.4281
2018						
13 June	155.7	151.9	146.8	146.3	4.33	0.3974
3 July	136.0	138.5	135.6	140.7	3.63	0.7419
18 July	127.8	129.1	133.5	131.3	3.14	0.6052
31 July	111.3	117.4	125.5	127.5	5.55	0.1993
15 August	118.0	128.9	126.3	124.3	4.72	0.4385
29 August	139.1	146.4	149.3	149.5	2.75	0.0651

^{abc} Means within a row without a common superscript differ ($P > 0.05$).

¹ TDN: Predicted total digestible nutrients = $(\text{NFC} \times 0.98) + (\text{CP} \times 0.87) + (\text{FA} \times 0.97 \times 2.25) + [\text{NDFn} \times (\text{NDFDp} \div 100)] - 10$ where NFC: nonfibrous carbohydrate (% of DM) = $100 - (\text{NDFn} + \text{CP} + \text{EE} + \text{ash})$, CP: crude protein (% of DM), FA: fatty acids (% of DM) = ether extract - 1, NDFn: nitrogen-free neutral detergent fiber (NDF) = NDF - NDFCP, also estimated as $\text{NDFn} = \text{NDF} \times 0.93$, NDFCP: neutral detergent fiber crude protein, NDFD: 48-hour in vitro NDF digestibility (% of NDF), and NDFDp: NDF digestible protein = $22.7 + .664 \times \text{NDFD}$.

² RFQ: Estimated relative forage quality = $\text{DMI} (\% \text{ of BW}) \times \text{TDN} (\% \text{ of DM}) / 1.23$.

Table 3.9. Least squares means of treatment (T) and year (Y) effects and their interaction on initial, midpoint, and final body weights (BW), total body weight gains (BWG), and period 1, 2, and total average daily gains (ADG) of forage-finished steers pastured on pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and pearl millet with soybean hull supplementation (BMR+S) during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Item	Treatment (T)				SEM	Year (Y)		SEM	P-Value		
	PM	PM+S	BMR	BMR+S		2017	2018		T	Y	T x Y
BW, kg											
Initial ¹	441	445	445	447	9.23	450	439	4.6	0.9532	0.1122	0.9874
Midpoint ¹	477	500	487	500	9.29	485	496	4.6	0.0591	0.0919	0.7014
Final ¹	493 ^b	538 ^a	498 ^b	538 ^a	10.4	513	520	5.2	<0.0001	0.3685	0.4670
BWG ² , kg	51.5 ^b	92.8 ^a	55.0 ^b	91.0 ^a	5.05	74.3	70.4	2.5	<0.0001	0.2274	0.0141
ADG, kg d ⁻¹											
Period 1 ³	0.74 ^b	1.08 ^a	0.93 ^{ab}	1.04 ^a	0.09	0.92	0.98	0.05	0.0017	0.2809	0.3303
Period 2 ⁴	0.40 ^b	0.98 ^a	0.28 ^b	0.99 ^a	0.07	0.67	0.66	0.06	<0.0001	0.7846	0.0429
Total ⁵	0.60 ^b	1.03 ^a	0.63 ^b	1.07 ^a	0.05	0.84	0.83	0.04	<0.0001	0.7994	0.0058

^{ab} Means within a row and effect grouping without a common superscript differ ($P < 0.05$).

¹ 2017: initial = 8 June, midpoint = 27 July, final = 7 September; 2018: initial = 13 June, midpoint = 31 July, final = 5 September.

² Treatment by year interaction presented in Table 3.10.

³ 2017 = 8 June – 26 July; 2018 = 13 June – 30 July.

⁴ 2017 = 27 July – 7 September; 2018 = 31 July – 5 September; Treatment by year interaction presented in Table 3.10.

⁵ Treatment by year interaction presented in Table 3.10.

Table 3.10. Least squares means of treatment by year effects on total body weight gains (BWG) and period 2 and total average daily gains (ADG) of forage-finished steers pastured on pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and pearl millet with soybean hull supplementation (BMR+S) during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Item/Year	Treatment				SEM	P-Value
	PM	PM+S	BMR	BMR+S		
BWG, kg						
2017	53.5 ^b	92.5 ^a	65.4 ^{ab}	85.9 ^a	8.66	0.0012
2018	50.2 ^b	93.0 ^a	41.7 ^b	96.8 ^a	6.76	<0.0001
ADG, kg d ⁻¹						
Period 2 ¹						
2017	0.49 ^b	0.92 ^a	0.39 ^b	0.89 ^a	0.10	<0.0001
2018	0.32 ^b	1.04 ^a	0.17 ^b	1.10 ^a	0.16	<0.0001
Total						
2017	0.59 ^b	1.03 ^a	0.73 ^b	0.95 ^a	0.10	0.0012
2018	0.60 ^b	1.11 ^a	0.50 ^b	1.15 ^a	0.08	<0.0001

^{abc} Means within a row without a common superscript differ ($P < 0.05$).

¹ 2017 = 27 July – 7 September; 2018 = 31 July – 5 September.

Table 3.11. Least squares means for treatment (T) and year (Y) effects and their interaction on live weight (LW), hot carcass weight (HCW), and other yield-related carcass characteristics of forage-finished steers pastured on pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and brown mid-rib pearl millet with soybean hull supplementation (BMR+S) during a grazing trial conducted during the summers of 2017 and 2018 at the University of Georgia Animal and Dairy Science Beef Research Unit near Eatonton, Georgia.

Item	Treatment (T)				SEM	Year (Y)			P-Value		
	PM	PM+S	BMR	BMR+S		2017	2018	SEM	T	Y	T x Y
LW ¹ , kg	484 ^b	521 ^a	494 ^{ab}	513 ^a	10.7	501	506	7.5	0.0043	0.4877	0.0162
HCW ² , kg	284 ^b	313 ^a	297 ^{ab}	309 ^a	7.51	303	298	5.3	0.0015	0.3281	0.0166
Dressing Percent, %	58.7	60.1	60.1	60.2	0.75	60.6 ^a	58.9 ^b	0.5	0.1521	0.0028	0.6837
Ribeye Area, cm ²	74.9	77.7	74.6	81.2	3.27	75.9	78.3	2.3	0.1698	0.3058	0.4529
KPH ³ , %	1.86 ^b	2.16 ^{ab}	2.11 ^{ab}	2.32 ^a	0.17	2.56 ^a	1.66 ^b	0.09	0.0470	<0.0001	0.2725
Fat Thickness, cm	0.63	0.79	0.61	0.70	0.10	0.74	0.63	0.07	0.2308	0.1086	0.9878
Adjusted FT, cm	0.68	0.79	0.66	0.78	0.07	0.80 ^a	0.65 ^b	0.07	0.4532	0.0340	0.9729
Yield Grade	2.21	2.46	2.35	2.29	0.16	2.56 ^a	2.08 ^b	0.16	0.7133	0.0036	0.7802

^{ab} Means within a row and effect grouping without a common superscript differ ($P < 0.05$).

¹ Treatment by year interaction presented in Table 3.12.

² Treatment by year interaction presented in Table 3.12.

³ KPH: percent kidney-pelvic-heart fat.

Table 3.12. Least squares means by year for treatment effects on live weight (LW) and hot carcass weight (HCW) of forage-finished steers pastured on pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and brown mid-rib pearl millet with soybean hull supplementation (BMR+S) during a grazing trial conducted during the summers of 2017 and 2018 at the University of Georgia Animal and Dairy Science Beef Research Unit near Eatonton, Georgia.

Item/Year	Treatment				SEM	P-Value
	PM	PM+S	BMR	BMR+S		
	LW, kg					
2017	492	507	506	496	17.6	0.7683
2018	477 ^b	535 ^a	482 ^b	530 ^a	12.0	0.0001
	HCW, kg					
2017	293	308	310	302	12.7	0.5655
2018	275 ^b	319 ^a	283 ^b	316 ^a	8.05	<0.0001

^{ab} Means within a row without a common superscript differ ($P < 0.05$).

Table 3.13. Least squares means for treatment (T) and year (Y) effects and their interaction on quality-related carcass characteristics of forage-finished steers pastured on pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and brown mid-rib pearl millet with soybean hull supplementation (BMR+S) during a grazing trial conducted during the summers of 2017 and 2018 at the University of Georgia Animal and Dairy Science Beef Research Unit near Eatonton, Georgia.

Item	Treatment (T)				SEM	Year (Y)			P-Value		
	PM	PM+S	BMR	BMR+S		2017	2018	SEM	T	Y	T x Y
Marbling Score ¹	384	402	421	397	28.3	392	410	20.0	0.6289	0.3618	0.7897
Lean Maturity ²	208 ^a	183 ^b	202 ^{ab}	189 ^{ab}	6.48	220 ^a	171 ^b	5.86	0.0335	<0.0001	0.5391
Skeletal Maturity ²	169	167	169	169	14.9	199 ^a	138 ^b	10.2	0.9979	<0.0001	0.9493
Overall Maturity ²	187	173	182	176	6.81	207 ^a	152 ^b	6.04	0.5400	<0.0001	0.7821
Lean Color ³	5.00 ^a	4.06 ^b	4.50 ^{ab}	4.25 ^{ab}	0.34	4.13 ^a	4.78 ^b	0.23	0.0488	0.0058	0.6708
Fat Color ⁴	2.81	2.84	2.66	2.82	0.34	2.59	2.97	0.22	0.8393	0.0962	0.5935
Lean Firmness ⁵	2.23	1.99	2.32	2.15	0.30	2.31	2.03	0.21	0.7263	0.1787	0.1588
Lean Texture ⁶	1.50	1.44	1.50	1.69	0.16	1.31 ^a	1.75 ^b	0.16	0.6923	0.0073	0.5543
Lean L* ⁷	37.9 ^a	40.2 ^{ab}	39.3 ^{ab}	40.3 ^b	0.88	40.1 ^a	38.8 ^b	0.62	0.0304	0.0339	0.5854
Lean a* ⁸	28.8	30.1	29.9	30.0	0.49	30.0	29.40	0.49	0.1856	0.2426	0.6588
Lean b* ⁹	20.4	21.9	21.7	21.7	0.78	21.7	21.15	0.54	0.1894	0.3105	0.6844
Fat L* ⁷	81.0	80.8	81.2	80.5	0.35	81.2	80.50	0.35	0.5530	0.0565	0.1101
Fat a* ⁸	9.03	9.38	8.90	10.0	0.56	8.6 ^a	10.06 ^b	0.40	0.2050	0.0008	0.0712
Fat b* ⁹	24.1	24.7	24.8	25.1	1.07	24.5	24.87	0.76	0.8203	0.6432	0.5382

^{ab} Means within a row and effect grouping without a common superscript differ ($P < 0.05$).

¹ 300 = Slight⁰⁰; 400 = Small⁰⁰; 500 = Modest⁰⁰.

² 100 = A⁰⁰; 200 = B⁰⁰.

³ 1 = light cherry red; 2 = bright cherry red; 3 = cherry red; 4 = slightly dark red; 5 = moderately dark red; 6 = dark red; 7 = very dark red. (Japanese Beef Lean and Fat Color Standards, The Japan Ham & Sausage Cooperative Association, Tokyo, Japan)

⁴ 1 = white; 2 = slightly creamy white; 3 = creamy white; 4 = slightly yellow; 5 = moderately yellow; 6 = yellow; 7 = very yellow. (Japanese Beef Lean and Fat Color Standards, The Japan Ham & Sausage Cooperative Association, Tokyo, Japan)

⁵ 1 = very firm; 2 = firm; 3 = slightly firm; 4 = slightly soft; 5 = soft.

⁶ 1 = very fine; 2 = fine; 3 = slightly fine; 4 = slightly coarse; 5 = coarse.

⁷ Objective measurement of lightness; 0 = darker; 100 = lighter.

⁸ Objective measurement of green to red; greater value indicates increased redness.

⁹ Objective measurement of blue to yellow; greater value indicates increased yellowness.

CHAPTER 4

GRAZING EVALUATION OF PEARL MILLET WITH AND WITHOUT SOYBEAN HULL
SUPPLEMENTATION II: MEAT QUALITY AND SIMULATED RETAIL DISPLAY²

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Abstract

A three-year study was conducted to evaluate pearl millet [*Pennisetum glaucum* (L.) R.Br. (PM)] and brown-midrib pearl millet (BMR) with and without supplementation of soybean [*Glycine max* (L.) Merr.] hulls (0.75% of body weight (BW); PM+S and BMR+S, respectively) for forage-finished beef production in the Southeastern U.S. Each year, Angus-cross bred steers ($n = 32$; 3-yr average BW = 439 ± 75 kg) were randomly assigned to treatments and finished for 64, 90, and 84 d during the summers of 2016, 2017, and 2018, respectively. Steers were harvested under USDA inspection in mid-September of each year. Striploins (longissimus lumborum) were removed from the right side of each carcass at 24 h postmortem, vacuum packaged, and wet aged for 21 d prior to sample fabrication. Samples were fabricated into 2.54-cm thick steaks and allocated to meats proximate, sensory, Warner-Bratzler shear force (WBSF), and simulated retail display analyses. Treatments had no effect ($P > 0.05$) on meats proximate analysis. Steaks from steers finished on PM+S were exhibited the greatest ($P = 0.0142$) sustained tenderness of all treatments but they were similar to PM and BMR+S steaks. Other sensory characteristics, thaw and cook losses, and WBSF were unaffected ($P > 0.05$) by treatments. Meat color data indicate no treatment held advantage over seven days of simulated retail display. However, PM steaks were darker ($P = 0.0076$) on day 2, and PM+S steaks were more yellow ($P = 0.0443$) than PM and BMR steaks on day 0. A similar pattern was observed for hue angle on day 0 ($P = 0.0424$). Furthermore, hue angle values of PM+S and BMR+S steaks were greater ($P = 0.0162$) than PM steaks on day 2 and only BMR+S steaks exhibited greater ($P = 0.0395$) hue angle than PM steaks on day 3. Deoxymyoglobin (DMb) concentrations were greater in PM steaks than steaks from supplemented steers on days 0, 1, 2, and 3 ($P = 0.0003$, $P = 0.0044$, $P =$

0.0014, and $P = 0.0017$, respectively) and greater than BMR steaks on days 2 and 3 ($P = 0.0014$ and $P = 0.0017$, respectively). On day 7 of display, BMR steaks had the greatest ($P = 0.0361$) Dmb concentrations but was not different from that of PM and PM+S steaks. Oxymyoglobin concentrations were greatest in PM+S steaks on day 0 ($P = 0.0026$) and BMR steaks on day 2 ($P = 0.0177$). Reflectance values for a^* , redness, chroma, metmyoglobin concentrations, were all unaffected ($P > 0.05$) by treatment. Results indicate that 'Exceed' BMR and 'Tifleaf 3' pearl millet can be used interchangeably in a Southeastern forage-finished beef production system with no or minimal impacts on chemical content, sensory attributes, and retail display characteristics of the ultimate beef product. Furthermore, soybean hull supplementation does not appear to improve sensory attributes, increase lipid content, or improve color or lipid stability during simulated retail display.

Introduction

Consumer acceptability and perceived value are of utmost importance in the beef industry. Organoleptic traits such as juiciness, flavor, and tenderness contribute to consumer's overall perception of value and satisfaction with meat products (Martin and Rogers, 2004). Presence of undesirable off flavors is often associated with forage-finished beef due to increased concentrations of diterpenoids in fat (Larick et al., 1987). Furthermore, several studies have cited a lack of intensity of desirable beef flavor of forage-finished beef (Mandell et al., 1997; Kerth et al., 2007; Garmyn et al., 2010). This has been attributed to reduced amounts of intramuscular fat arising from a lower plane of nutrition when compared with grain-finished beef (Duckett et al., 2013; Acheson et al., 2014). Supplementation of grazing animals with non-protein feedstuffs has been proposed as a method to increase beef flavor intensity by elevating the nutritional plane and reducing the presence and intensity of off flavors by reductions in the production of diterpenoids from chlorophyll in the rumen by microorganisms (Griebenow et al., 1996). There is a gap in the literature of studies reporting on the effects of finishing cattle on pearl millet (*Pennisetum glaucum* L.R. Br.) with and without soybean [*Glycine max* (L.) Merr.] hull supplementation on organoleptic traits. Furthermore, the examination of suitability of a beef-finishing system is incomplete without information on tenderness, juiciness, and flavor of the ultimate beef product. Correlation of these subjective traits with objective measurements of tenderness and chemical fractions of meat is necessary to support subjective findings of a sensory panel.

Although taste and tenderness are critical factors dictating the eating satisfaction of beef, the appearance of fresh beef is a determinate of purchase intent (Carpenter et al., 2001). Consumers are attracted to beef products that exhibit bright, cherry-red color. Meat that is dark-

red or brown in appearance is often discounted or removed from retail displays leading to economic loss (Suman and Joseph, 2013). As a result, color stability is an important factor in determining economic viability of a meat product. Lipid oxidation is a process that is positively correlated with the change in color of meat from bright, cherry-red to darker, brick-red to brown. The mechanism of this relationship is the production of free-radical, oxidizing agents via lipid oxidation that hasten protein oxidation of the myoglobin molecule (Faustman et al., 1999). The products of lipid oxidation are also responsible for undesirable rancid, off flavors and odors (Pearson et al., 1977). Therefore, measuring the amount of lipid oxidation is important to the determination of the retail viability of a meat product. No information is currently available in the literature on the degree of lipid oxidation of beef steaks from cattle finished on pearl millet pastures with and without soybean hull supplementation.

The objective of this study was to examine the effects of finishing diet on organoleptic traits via a trained sensory panel and to evaluate the instrumental tenderness and chemical content of beef steaks from steers finished on two varieties of pearl millet with and without soybean hull supplementation. Furthermore, factors associated with meat color as well as degree of lipid oxidation of beef steaks from steers finished on two varieties of pearl millet with and without soybean hull supplementation displayed for 7 d in typical retail fashion were examined.

Materials and Methods

The experimental procedures involving human subjects were reviewed and approved by the University of Georgia Institutional Review Board (Protocol #STUDY00000623).

Finishing Treatments

The steers used in this project were part of a greater project examining the use of pearl millet grazing with and without soybean hulls for forage finished beef systems. For a full description of forage planting, forage quality, animal performance, and carcass characteristics see Chapter 3. Briefly, in each of three years, Angus-cross bred steers ($n = 32$; 3-yr average BW = 439 ± 75 kg) were randomly assigned to one of four finishing treatments that were arranged in a 2x2 factorial design. The treatments were as follows: ‘Tifleaf 3’ pearl millet (PM) and ‘Exceed’ BMR pearl millet (BMR) without soybean hull supplementation (PM and BMR, respectively) and with soybean supplementation at a rate of 0.75% BW d^{-1} (PM+S and BMR+S, respectively). Steers were finished for a total of 64, 90, and 84 d during the summers of 2016, 2017, and 2018, respectively at the University of Georgia Department of Animal and Dairy Science Beef Research Unit located near Eatonton, GA. The steers from 2016 were removed from the analyses due to inadequate pearl millet establishment in all paddocks.

Animal Harvest and Sample Fabrication

Steers were slaughtered under USDA inspection in two groups on the 14 and 15, and 11 and 13 September of 2017, and 2018, respectively with slaughter groups balanced by treatment. Twenty-four hours postmortem and after carcass grade data were collected (Chapter 3) the whole boneless strip loin (longissimus lumborum; Institutional Meat Purchase Specifications #180) was removed from the right side of each carcass. Strip loins were vacuum packaged (30 to 50 mL of $O_2/m^2/24$ h; $101,325$ Pa; $23^\circ C$; B-620 series, Cryovac Sealed Air Corporation, Charlotte, NC) and stored at $0 \pm 2^\circ C$ in waxed cardboard boxes for 21 d of wet aging. At the end of the aging period, the strip loins were fabricated into steaks (2.54-cm thick). Steaks were allocated to analyses from anterior to posterior in the following manner: proximate and fatty acids ($n = 1$),

Warner-Bratzler shear force (WBSF; $n = 2$), trained sensory panel ($n = 2$), and simulated retail display objective color and lipid oxidation ($n = 8$). Except for those allocated to simulated retail display analyses, all steaks were vacuum packaged and stored ($-20 \pm 2^\circ\text{C}$) until analyses were performed.

Proximate Analysis

Proximate analysis was conducted to determine moisture, protein, fat, and ash content of each sample. Steaks were thawed at $2 \pm 2^\circ\text{C}$ for approximately 24 h, trimmed to remove all external fat and visible connective tissue, minced, placed in liquid nitrogen (-129°C), and powder-homogenized using a commercial blender (Waring Commercial Products, McCConnellsburg, PA). Percent moisture was analyzed by drying crucibles in a 90°C forced-air oven for 12 h before being removed and cooled in a desiccator. Once cooled, empty crucible weight was recorded, and 3 ± 0.05 g of homogenized sample was measured in duplicate. Crucibles were then placed into a forced-air oven (90°C) and allowed to dry to a constant weight. Once dry, samples were placed into a desiccator for 10 min before a final dry weight was recorded for the determination of moisture content as described by AOAC, 2000. Dry samples were then placed into a 500°C cool muffle furnace until constant weight was achieved. Crucibles were removed from the oven, placed in a desiccator to cool and weighed for the determination of inorganic ash content. Determination of inorganic ash content was calculated by the difference in weight as described by AOAC (2000).

Percent lipid content of samples was measured following the procedure described by Folch et al. (1957) where total lipid content was extracted from samples in duplicate.

Approximately 1 ± 0.1 g of powder homogenized meat sample was placed into dried extraction tubes with 8.1 mL of a mixture of 3.5:1 methanol: water. Samples were vortexed for 15 s prior to the addition of 3.25 mL of chloroform and vortexed for an additional 20 s. A Burrell Wrist Action Shaker (Model 75; Burrell Corp., Pittsburgh, PA) was then used to mix the samples for 1 h before 3.8 mL of chloroform and 3.8 mL of aqueous KCl (0.37%) were added. Samples were then centrifuged for 20 min at $2250 \times g$ (IEC HN SII Centrifuge, International Equipment Co., Ramsey, MN) and the upper aqueous layer was aspirated. Five milliliters of aqueous KCl (0.37%) was then added and the centrifuge and aspiration processes were repeated. A Buchner funnel with a Whatman #1 (4.25 cm) filter paper was then used to filter samples into clean vials. Samples were then evaporated in vials under gaseous nitrogen (N_2) to an approximate volume of 2 mL and transferred to 10 mL volumetric flasks. Each sample was then brought to 10-mL volume with chloroform and transferred to screw-top amber glass vials. Two milliliters of extract were pipetted into dried and weighed 12- x 75-mm culture tubes in duplicate. Each screw-top vial was flushed with N_2 prior to storage at $-20 \pm 2^\circ C$ for future fatty acid analysis. Culture tubes were evaporated under N_2 prior to being placed into a forced air oven ($60^\circ C$) for 30 min. After drying, samples were cooled in a desiccator for 10 min prior to the recording of a final weight. Percent lipid was calculated by the following equation: Percent lipid = $[(\text{tube + lipid weight})/\text{tube weight}] \times 5 / \text{wet tissue weight}] \times 100$.

Percent protein was calculated indirectly by subtracting the total estimates of lipid, ash, and moisture percent from 100.

Cooking Characteristics and Instrumental Tenderness

Instrumental tenderness was measured by Warner-Bratzler shear force analysis conducted in accordance to AMSA guidelines (2016). Two steaks from each striploin were removed from packaging, weighed frozen in pairs, thawed at $2 \pm 2^{\circ}\text{C}$, and weighed again in pairs to calculate thaw loss. All steaks were then cooked to an internal temperature of 71°C on clamshell-style grills (George Foreman Grills, Spectrum Brands, Madison, WI) and weighed in pairs to calculate cook loss. Initial and final cooking temperature were measured with copper constantan thermal couplers (Omega Engineering, Stamford, CT) placed in the geometric center of each steak and monitored with a scanning thermocouple meter (Digi-Sense, Cole-Parmer, Vernon Hills, IL). Cooking time was also recorded. After being cooked steaks were placed on poly trays, wrapped with PVC foodservice film (Reynolds Consumer Products, Lake Forest, IL) and stored ($2 \pm 2^{\circ}\text{C}$) for 24 h. Once cooled, six 1.27-cm cores were taken from each pair of steaks parallel to muscle fibers with a handheld coring device. Cores were then sheared perpendicular to the long axis of the muscle fibers using an Instron Universal Testing Machine (Instron Dual Column Model 3365, Instron Corporation, Norwood, MA) with a Warner-Bratzler shear head, 51 kg-f load cell with a crosshead speed of 25 cm min^{-1} . The peak shear force for each core was recorded (Bluehill software, Instron Corporation) and an average value was determined for each pair of steaks.

Trained Sensory Panel Analysis

Trained sensory panel analysis for initial and sustained tenderness, beef flavor intensity, juiciness, and the presence and intensity of off flavors was conducted in accordance to the guidelines of AMSA (2016). Cookery methods used for sensory analysis were similar to those used for Warner-Bratzler shear force analysis. After cooking, samples were prepared for

panelists by removing all subcutaneous fat and visible connective tissue from each steak. Steaks were then cut to a sample size of 1.27 cm x 1.27 cm x steak thickness in a sample sizer (AMSA, 2016). Cut samples were then placed in pre-warmed glass jars in yogurt makers (Euro Cuisine, Inc., Los Angeles, CA) until sampled. Two pieces of meat per pair of steaks were served to each panelist with distilled water and unsalted soda crackers to cleanse panelists' palates between samples. Two sensory panel sessions were held each day with approximately 3 h between the start of the first and second sessions. Seven samples were provided at each session along with a warm-up sample. Sensory panelists (n = 8) were seated in a positive airflow room that was illuminated with red-tinted light to control for outside odors and variability in sample color, respectively. Samples were passed to each panelist through breadbasket-style dividers with walls separating each panelist. Panelists were asked to evaluate each sample for initial and sustained tenderness, beef flavor intensity, juiciness (1 - extremely tough, extremely bland, extremely dry, and 8 - extremely tender, extremely intense, extremely juicy) and intensity of off-flavors (1 – none detected, and 6 – extreme off-flavor).

Simulated Retail Display: Objective Color and Lipid Oxidation

Immediately following strip loin fabrication, steaks allocated to simulated retail display and lipid oxidation analysis were randomly assigned to one of eight days of simulated retail display (D0 through D7). Steaks were placed on absorbent pads (Dri-Loc AC-40, Cryovac Sealed Air, Charlotte, NC) in 2S Styrofoam trays and wrapped with an oxygen permeable polyvinylchloride (PVC) overwrap (O_2 transmission = 23,250 mL/m²/24 h, 72 gauge; Pro Pack Group, Oakland, NJ). Steaks were then placed in open-top, coffin-style retail cases with a defrost cycle every 12 h ($0 \pm 2^\circ\text{C}$; MIX-E, Hussmann, Bridgeton, MO). Steaks were kept under 24-h

warm white fluorescent lighting (1600 to 1900 lux; Octron/ECO; 30000K; F032/830/ECO; Sylvania Company, Versailles, KY) and rotated within the cases daily. Retail case temperature was monitored and recorded by continuous data loggers (TR-52ui, T&D Corp., Japan) placed at package height.

Objective color readings were taken on unopened, packaged D7 steaks at 24-h intervals starting with initial readings at approximately 1 h after fabrication. A Hunter-Lab MiniScan XE colorimeter (Hunter Associates Laboratory, Inc.) with illuminate A, 10° viewing angle, and a 2.54-cm aperture was used. The colorimeter was standardized using a white tile standard and black tile standard prior to each daily use. Readings were taken in triplicate from different 50-mm diameter areas of each packaged steak that were then averaged to obtain final values for each sampling day. *Commission Internationale de l'Eclairage* (CIE) L^* (lightness), a^* (redness), and b^* (yellowness) were measured to determine color change from d_0 (ΔE ; Equation 1). Values for hue and chroma were then calculated for each day of simulated retail display (Equations 4.2 and 4.3, respectively). Reflectance readings (R) were taken at 474 nm, 525 nm, 572 nm, 580 nm, 610 nm, 630 nm, and 700 nm. These values were transformed to absorbance values (A) using Equation 4.4. Estimates of percent deoxymyoglobin (DMb) and metmyoglobin (MMb) were calculated for each day of simulated retail display using the Equations 4.5 and 4.6, respectively. Percent oxymyoglobin (OMb) was calculated indirectly for each day of simulated retail display as the difference of 100 and the sum of DMb and MMb, (Equation 4.7). Redness due to OMb or DMb was calculated for each day of simulated retail display using the ratio $R_{630}:R_{580}$ (AMSA, 2012).

Steaks were removed from the retail cases and packaging in 24-h intervals according to previously assigned day of simulated retail display, individually vacuum packaged, and stored ($20 \pm 2^\circ\text{C}$) until lipid oxidation analysis could be performed.

Equation 4.1: Calculation of change in color (ΔE_d) where d = days since fabrication, L^* = lightness, a^* = redness, and b^* = yellowness

$$\Delta E_d = \sqrt{(L_0^* - L_d^*)^2 + (a_0^* - a_d^*)^2 + (b_0^* - b_d^*)^2}$$

Equation 4.2: Calculation of hue (H^*) where redness = a^* and yellowness = b^* .

$$H^* = \left(\arctangent \frac{b^*}{a^*} \right) * \frac{180}{3.142}$$

Equation 4.3: Calculation of chroma (C^*) where redness = a^* and yellowness = b^* .

$$C^* = \sqrt{a^{*2} + b^{*2}}$$

Equation 4.4: Calculation of absorbance values (A) from reflectance values (R) at a given wavelength, in decimal form.

$$A = \frac{1}{\log R}$$

Equation 4.5: Calculation of percent deoxymyoglobin (%DMb) from absorbance values (*A*) at 473 nm, 525 nm, and 700 nm.

$$\%DMb = 100 * \left\{ 2.375 * \left[1 - \frac{(A_{473} - A_{700})}{(A_{525} - A_{700})} \right] \right\}$$

Equation 4.6: Calculation of percent metmyoglobin (MMb) from absorbance values (*A*) at 572nm, 525nm, and 700nm.

$$\%MMb = 100 * \left\{ 1.395 - \left[\frac{(A_{572} - A_{700})}{(A_{525} - A_{700})} \right] \right\}$$

Equation 4.7: Calculation of percent oxymyoglobin (OMb) from %DMb and %MMb values

$$\%OMb = 100 - (\%MMb + \%DMb)$$

Lipid oxidation was determined for simulated retail display steaks by thiobarbituric acid reactive substances (TBAR) assay for malonaldehyde (MDA) and other aldehyde products of lipid oxidation according to the procedures outlined in the American Meat Science Association Meat Color Measurement Guidelines Handbook (Sinnhuber and Yu, 1958; Buege and Aust, 1978; AMSA, 2012). Briefly, steaks were thawed at 4°C for 24 h, removed from packaging and trimmed of all subcutaneous fat and connective tissue. Samples were then finely minced and mixed to form a homogenous sample. Samples of 0.5-0.515 g of meat were weighed in duplicate and placed in 16 x 100-mm borosilicate glass test tubes. Remaining meat sample was repackaged, vacuum sealed, and kept frozen pending further analysis. To each tube 2.5 mL of a stock solution consisting of 0.375% thiobarbituric acid, 15% trichloroacetic acid, and 0.25 N

HCl in deionized water was added. Tubes were then vortexed for 1 min and incubated for 10 min in a 100°C water bath for color development. Tubes were removed from the water bath and cooled in tap water. Tubes were then centrifuged at 5,000 x g for 10 min at 4°C to obtain the supernatant. The supernatant was then pipetted into 12- x 75-mm borosilicate glass test tubes. The absorbance of the supernatant at 532 nm was measured using a spectrophotometer (V-630 UV-Visible/NIR, Jasco Analytical Instruments, Easton, MD). Milligrams of MDA kg⁻¹ meat was calculated by multiplying the absorbance at 532 nm by a factor of 2.77.

Statistical Analysis

All data were analyzed using PROC GLIMMIX of SAS v. 9.4 (SAS Institute, Cary, NC). Means were separated using the LSMEANS statement with the PDIFF option. Statistical significance was set at $\alpha = 0.05$ and *P*-values were adjusted for multiple comparisons using Tukey's HSD adjustment. For all analyses loin was considered the experimental unit with steak serving as the observational unit and year was included as a random blocking term. The analysis of simulated retail display color and lipid oxidation also included the effect of day of display and the interaction of treatment by day of display. If an interaction was detected the data were reanalyzed by day to discern difference within day of display.

Results and Discussion

Meats Proximate Analysis

Treatment had no effect on the proportions of protein, lipid, moisture, or ash of strip loins ($P = 0.8350$, $P = 0.1607$, $P = 0.0859$, and $P = 0.7985$, respectively; Table 4.1). Given the

increased energy provided to supplemented treatment steers, increased lipid content was expected for the steaks from these animals, but this effect was not observed. Lipid content of steaks from all treatments was greater than the 2.30 and 2.55% reported by Schmidt et al. (2013) and Harmon (2017), respectively, for steaks from steers finished on pearl millet. Moisture content for all treatments in the present study was lesser than the values reported by Schmidt et al. (2013) and Harmon (2017), 76.14 and 73.9%, respectively, which is likely due to the discrepancies in lipid content between the present study and those two studies. Protein content was greater across all treatments in the present study than the protein content for steaks from pearl millet-finished carcasses reported by Schmidt et al. (2013) and Harmon (2017) (22.62 and 22.5%, respectively). Ash content of all treatments in the present study was less than the values of 1.59 and 1.11% reported by Schmidt et al. (2013) and Harmon (2017), respectively, for steaks from pearl millet-finished beef carcasses. However, Schmidt et al. (2013) and Harmon (2017) did not report any treatment differences ($P > 0.05$) due to forage type on protein, lipid, moisture, nor ash content of forage-finished beef steaks, similar to the findings of the present study.

Cooking Characteristics, Instrumental Tenderness, and Trained Sensory Panel Analysis

No differences were observed for thaw or cook losses ($P = 0.1189$ and $P = 0.1301$, respectively; Table 4.2) which is expected given moisture and lipid content did not differ across treatments. No difference ($P = 0.6366$) was observed for peak force values (kgf) as measured by Warner-Bratzler shear force analysis (WBSF). Steers used on this study were all less than two years in age at time of slaughter and treatment effects on lipid content were not observed. Therefore, we would not expect to see treatment effects on instrumental tenderness.

Results for the trained sensory panel analysis are presented in Table 4.2. No treatment effect ($P = 0.2254$) was observed for initial tenderness but panelists scored steaks from steers finished on PM+S to have greater sustained tenderness ($P = 0.0142$) than steaks from steers finished on BMR. However, panelist scores for sustained tenderness were between 5 and 6 (slightly tender and moderately tender, respectively) for all treatments and given the lack of treatment effects on instrumental and initial tenderness, these findings, while statistically significant, are likely of minimal practical importance. Beef flavor intensity was unaffected ($P = 0.7097$) by treatments with panelists rating steaks from all treatments slightly to moderately intense. Given the lack of treatment effects on lipid content ($P = 0.1607$; Table 4.1) and the positive relationship between fatness and beef flavor intensity, (Duckett et al. 2013; Acheson et al. 2014), differences in beef flavor intensity were not expected. Treatments had no effect ($P = 0.1638$) on juiciness scores. This result is corroborated by the lack of treatment differences for moisture and lipid content as well as thaw and cook losses.

Forage-finished beef is often associated with off-flavors (Larick et al., 1987). However, in the present study, off-flavors were not detected or were of minimal intensity for all treatments ($P = 0.2666$). Furthermore, soybean hull supplementation did not reduce the intensity of off flavors as proposed by Griebenow et al. (1996). Melton (1983) suggested utilization of forages of good quality reduces the likelihood and intensity of off-flavors in forage-finished beef. Martin and Rogers (2004) proposed increased carcass fatness reduces the concentration of off-flavor-producing volatiles accreted in the fat via dilution. Since flavor has emerged as an important valuation factor for consumers, utilization of forages of good quality, such as pearl millet, in commercial forage-finishing operations may ensure consumer acceptability and satisfaction.

Simulated Retail Display: Objective Color and Lipid Oxidation

Due to the only treatment by day interaction being percent Dmb (Figure 4.1; $P = 0.0121$), data are presented by the main effects of treatment (Table 4.3) and day (Table 4.4). As expected, day of display impacted all objective color measurements ($P < 0.0001$) with samples becoming darker (L^*) and less red (a^* , 580:630, hue angle). Delta E also increased with time of display and corresponds to a decrease in the vividness (Chroma) of the samples. The change in color can be explained by the changes in the proportions in Dmb, Omb, and Mmb where Omb decreased over time in display while Dmb and Mmb increased ($P < 0.0001$). Additionally, TBARs increased from D0 to D2 ($P < 0.0001$) and leveled out with no further increase out to D7. The reactive by-products of lipid oxidation have been shown to accelerate myoglobin oxidation, resulting in reduced color stability (Faustman et al., 1999). However, in the present study lipid oxidation plateaued at D2 while color continued to deteriorate, suggesting free radicals generated via lipid oxidation played only a minor role in color change over the simulated retail display period. Faustman et al. (1989) and Daley et al. (2010) proposed leanness and α -tocopherol or vitamin E, an antioxidant, content of forage-finished beef products increased lipid stability despite having elevated levels of polyunsaturated fatty acids. This could explain the lipid stability exhibited by samples on D2 through D7 in the present study; however, it is likely that lipid oxidation was limited to the exterior of the samples, restricting MDA formation.

Holman et al. (2017) correlated several metrics of instrumental beef color with consumer acceptability. They reported a^* as the strongest predictor of consumer preference with an acceptability threshold minimum of 12.5 for a 90% confidence interval. Steaks from all treatments in the present study exhibited a^* values of greater than 12.5 throughout the simulated

retail display analysis, indicating all treatments maintained consumer color acceptability throughout the seven days of display.

Examining the main effect of treatment there was no effect on a^* , ΔE , hue angle, redness, percent Mmb, or MDA concentration ($P > 0.05$). However, samples from PM were darker (L^*) than samples from all other treatments and BMR was darker than PM+S ($P < 0.0001$). Chroma indicated that PM+S was more vivid than PM ($P = 0.0116$) but BMR and BMR+S were similar to all samples. Percent Omb of PM+S was greater ($P = 0.0031$) than BMR and PM but similar to BMR+S, indicating supplementation with soybean hulls may increase Omb content over seven days of simulated retail display.

As stated percent Dmb was the only treatment by day interaction ($P = 0.0120$; Figure 4.1) and showed that PM had a greater proportion of Dmb than PM+S and BMR+S on D0 and D1 ($P = 0.0003$ and $P = 0.0044$, respectively), and more than PMS, BMRS and PMS on D2 and D3 ($P = 0.0014$ and $P = 0.0017$, respectively). There was no difference ($P > 0.05$) on D4, D5, and D6, but on D7 BMR had a greater ($P = 0.0361$) proportion of Dmb than BMR+S.

Conclusions

‘Exceed’ BMR and ‘Tifleaf 3’ pearl millet can be used interchangeably in a Southeastern forage-finished beef production system with no or minimal impacts on chemical content, sensory attributes, and lipid and color stability of the ultimate beef product. Furthermore, soybean hull supplementation does not appear to improve sensory attributes, increase lipid content, or improve stability during retail display. Decreased lipid content of pearl millet-finished beef may limit

lipid oxidation in retail display scenarios however, more research is needed to explore the roles of lipid type and α -tocopherol in these phenomena.

Acknowledgments

This project was supported in part by the Georgia Agricultural Commodity Commission for Beef and the United States Department of Agriculture National Institute of Food and Agriculture, Agriculture and Food Research Initiative CARE program 2016-68008-25145.

Conflict of interest statement. None declared.

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Table 4.1. Least squares means for treatment effects on percentages of protein, lipid, moisture, and ash for longissimus muscle samples taken from carcasses of forage-finished steers pastured on pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and pearl millet with soybean hull supplementation (BMR+S) during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

	Treatment				SEM	<i>P</i> -Value
	PM	PM+S	BMR	BMR+S		
Protein, %	23.7	23.8	23.5	23.7	0.18	0.8350
Lipid, %	3.24	4.20	4.22	4.26	0.26	0.1607
Moisture, %	72.0	71.0	71.3	71.0	0.33	0.0859
Ash, %	1.04	1.06	1.04	1.05	0.02	0.7985

Table 4.2. Least squares means for treatment effects on cooking characteristics, Warner-Bratzler shear force (WBSF), and sensory scores from trained sensory panel analysis of striploin steaks from forage-finished steers pastured on pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and pearl millet with soybean hull supplementation (BMR+S) during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Item	Treatment				SEM	<i>P</i> -Value
	PM	PM+S	BMR	BMR+S		
Thaw Loss, %	1.02	0.34	0.80	0.61	0.29	0.1189
Cook Loss, %	12.8	14.5	11.7	12.3	1.19	0.1301
WBSF, kgf	3.30	3.23	3.11	3.27	0.12	0.6366
Initial Tenderness ¹	5.51	5.66	5.45	5.32	0.24	0.2254
Sustained Tenderness ¹	5.77 ^{ab}	5.99 ^a	5.52 ^b	5.55 ^{ab}	0.24	0.0142
Beef Flavor Intensity ¹	5.08	5.12	5.14	5.19	0.16	0.7097
Juiciness ¹	4.43	4.76	4.80	4.57	0.20	0.1638
Off-Flavor Intensity ²	1.15	1.16	1.29	1.22	0.12	0.2666

^{ab} Means within a row and effect grouping without a common superscript differ ($P < 0.05$).

¹ 1 = extremely tough, bland, dry; 2 = very tough, bland, dry; 3 = moderately tough, bland, dry; 4 = slightly tough, bland, dry; 5 = slightly tender, intense, juicy; 6 = moderately tender, intense, juicy; 7 = very tender, intense, juicy; 8 = extremely tender, intense, juicy.

² 1 = none detected; 2 = threshold off-flavor; 3 = slight off-flavor; 4 = moderate off-flavor; 5 = very strong off-flavor; 6 = extreme off-flavor.

Table 4.3. Least squares means for treatment effects on instrumental color characteristics and malondialdehyde (MDA) concentrations of striploin steaks subjected to 0 through 7 days of simulated retail display from forage-finished steers pastured on pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and pearl millet with soybean hull supplementation (BMR+S) during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Item	Treatment				SEM	P-Value
	PM	PM+S	BMR	BMR+S		
L* ¹	38.3 ^c	40.7 ^a	39.8 ^b	40.0 ^{ab}	0.34	<0.0001
a* ²	27.2	28.2	27.4	27.9	0.39	0.0633
b* ³	20.7 ^b	21.8 ^a	21.0 ^{ab}	21.6 ^a	0.31	0.0007
Delta E ⁴	7.54	6.61	6.69	6.82	0.51	0.2401
Hue	37.3	37.7	37.5	37.9	0.26	0.0834
Chroma	34.2 ^b	35.6 ^a	34.5 ^{ab}	35.3 ^{ab}	0.48	0.0116
Redness	5.37	5.38	5.23	5.26	0.14	0.6181
Dmb, % ⁵	6.7 ^a	4.56 ^b	7.68 ^a	4.71 ^b	0.76	<0.0001
Omb, % ⁶	66.5 ^b	69.3 ^a	66.2 ^b	68.6 ^{ab}	1.00	0.0031
Mmb, % ⁷	26.8	26.2	26.1	26.7	0.60	0.5153
MDA, mg kg ⁻¹	0.19	0.20	0.19	0.20	0.01	0.5678

^{abc} Means within a row without a common superscript differ ($P < 0.05$).

¹ Measurement of lightness; 0 = darker; 100 = lighter.

² Measurement of green to red; greater value indicates increased redness.

³ Measurement of blue to yellow; greater value indicates increased yellowness.

⁴ Calculation of change in color from day 0.

⁵ Percent deoxymyoglobin. Treatment by day interaction ($P = 0.0120$) presented in Figure 4.1.

⁶ Percent oxymyoglobin.

⁷ Percent metmyoglobin.

Table 4.4. Least squares means for day effects on malondialdehyde (MDA) concentrations and instrumental color characteristics of striploin steaks subjected to 0 through 7 days of simulated retail display from forage-finished steers pastured on pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and pearl millet with soybean hull supplementation (BMR+S) during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

Item	Day of Simulated Retail Display								SEM	P-Value
	0	1	2	3	4	5	6	7		
L* ¹	41.8 ^a	41.3 ^{ab}	40.8 ^{ab}	40.2 ^{bc}	39.8 ^{bc}	38.8 ^{dc}	37.9 ^{de}	37.0 ^e	0.48	<0.0001
a* ²	31.8 ^a	31.4 ^{ab}	30.1 ^{bc}	29.6 ^{dc}	28.0 ^{de}	26.4 ^e	23.6 ^f	20.6 ^g	0.56	<0.0001
b* ³	23.8 ^a	23.9 ^a	22.8 ^{ab}	22.4 ^{bc}	21.3 ^{dc}	20.4 ^d	18.5 ^e	16.9 ^f	0.44	<0.0001
Delta E ⁴	-	2.41 ^e	3.5 ^e	4.2 ^{de}	5.68 ^{cd}	7.56 ^c	10.8 ^b	14.2 ^a	0.67	<0.0001
Hue	36.7 ^c	37.2 ^{bc}	37.1 ^{bc}	37.1 ^{bc}	37.2 ^{bc}	37.9 ^{bc}	38.2 ^b	39.4 ^a	0.37	<0.0001
Chroma	39.7 ^a	39.5 ^a	37.7 ^{ab}	37.1 ^{bc}	35.2 ^{cd}	33.4 ^d	30.0 ^e	26.7 ^f	0.68	<0.0001
Redness	7.07 ^a	6.54 ^b	6.02 ^c	5.9 ^c	5.27 ^d	4.76 ^e	3.86 ^f	3.06 ^g	0.19	<0.0001
Dmb, % ⁵	1.55 ^e	2.21 ^e	3.22 ^{de}	3.6 ^{de}	4.37 ^d	6.51 ^c	10.9 ^b	15.0 ^a	1.07	<0.0001
Omb, % ⁶	79.9 ^a	75.4 ^b	73.1 ^{bc}	72.1 ^{bc}	69.3 ^{cd}	65.1 ^d	57.3 ^e	48.9 ^f	1.41	<0.0001
Mmb, % ⁷	18.5 ^f	22.4 ^e	23.7 ^e	24.3 ^{de}	26.3 ^{cd}	28.4 ^c	31.8 ^b	36.2 ^a	0.84	<0.0001
MDA, mg kg ⁻¹	0.14 ^b	0.18 ^{ab}	0.22 ^a	0.19 ^a	0.20 ^a	0.20 ^a	0.22 ^a	0.21 ^a	0.03	<0.0001

abcdefg Means within a row without a common superscript differ ($P < 0.05$).

¹ Measurement of lightness; 0 = darker; 100 = lighter.

² Measurement of green to red; greater value indicates increased redness.

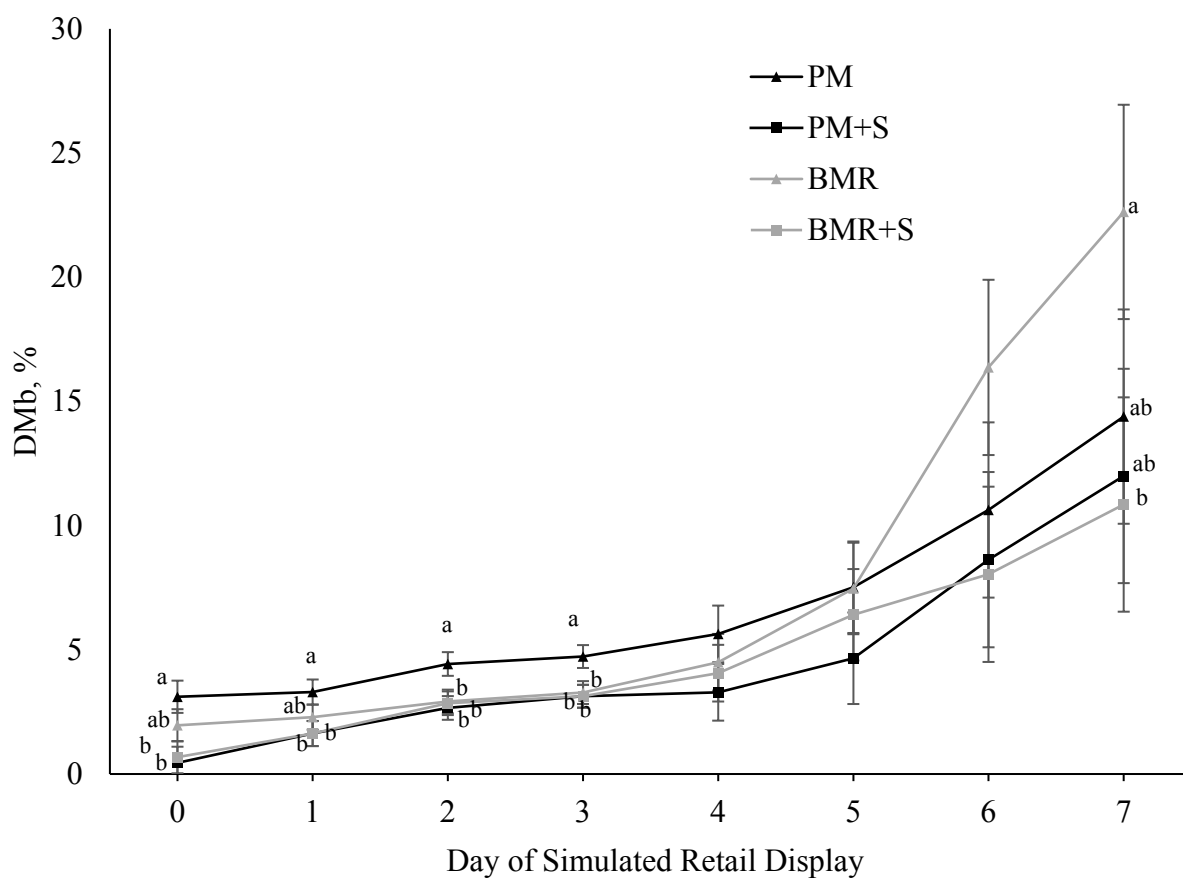
³ Measurement of blue to yellow; greater value indicates increased yellowness.

⁴ Calculation of change in color from day 0.

⁵ Percent deoxymyoglobin. Treatment by day interaction ($P = 0.0120$) presented in Figure 4.1.

⁶ Percent oxymyoglobin.

⁷ Percent metmyoglobin.



	0	1	2	3	4	5	6	7
<i>P</i> -Value	0.0003	0.0044	0.0014	0.0017	0.2302	0.3754	0.0846	0.0361
SE	0.6493	0.5055	0.4769	0.4605	1.1411	1.8419	3.528	4.3147

Figure 4.1. Least square means for the interaction of treatment¹ and day² ($P = 0.0120$) on deoxymyoglobin (DMb) concentrations of striploin steaks subjected to 0 through 7 days of simulated retail display from forage-finished steers pastured on pearl millet (PM), pearl millet with soybean hull supplementation (PM+S), brown mid-rib pearl millet (BMR), and pearl millet with soybean hull supplementation (BMR+S) during the summers of 2017 and 2018 at the University of Georgia Department of Animal and Dairy Science Eatonton Beef Research Unit near Eatonton, Georgia.

¹ Main effects of treatment $P < 0.0001$.

² Main effects of day $P < 0.0001$.

^{ab} Means within day without common superscript differ ($P < 0.05$).

CHAPTER 5

CONCLUSIONS AND IMPLICATIONS

This study found pearl millet to be a viable warm-season forage option for forage-finished beef production systems in the southeastern U.S. Animal performance was adequate for achieving typical forage-finished slaughter weights in approximately 90 d given initial weights of approximately 440 kg. Supplementation of soybean hulls to animals grazing pearl millet can improve animal performance and brighten lean color thereby reducing carcass lean maturity scores. Soybean hull supplementation was not found to increase stocking rates or forage mass of grazed pastures in the present study. In general, carcass and meat quality were largely unaffected by treatments, but all treatments achieved USDA quality grades at the Select – Choice interface. The achievement of economical slaughter weights and adequate carcass fat cover at animal ages of less than two years might be crucial in ensuring forage-finished beef is of acceptable quality, particularly in reference to tenderness, juiciness, and the presence and intensity off-flavors. Despite not improving meat quality in the present study, supplementation with soybean hulls could reduce animal age at economical slaughter weights via improvements in average daily gains, reducing the likelihood of maturity-associated impairments on meat quality. This information will serve producers that are seeking to improve animal performance during the summer months as well as produce high-quality, forage-finished beef regardless of the season. More research is needed to determine the role of forage variety and supplementation status on fatty acid and α -tocopherol content of pearl millet-finished beef products. Furthermore, the

economic viability of pearl millet-based forage-finished beef production systems needs to be determined in order to assist producers in making fiscal and marketing decisions.