Evaluating teff grass as a summer forage

by

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Abstract

Finding a high-value forage crop with limited water requirements to produce livestock feed is becoming increasingly important as producers adapt to restricted water supply conditions. Our objectives were to determine the forage yield, nutritive values, and crop water productivity (CWP) of teff grass (*Eragrostis tef* [Zucc.] Trotter) under field conditions when compared to sorghum sudangrass (SS, *S. x drummondii*[(Nees ex. Steud.) Millsp. & Chase]) and pearl millet (PM, *P. glaucum* [L.]R.Br.). Crop water productivity was determined by dividing above-ground biomass by crop water use. Crop water use was determined by the summation of soil water depletion, precipitation, and irrigation. Yield was determined by quadrat area clippings of above-ground biomass. Nutritive value was determined using wet chemical analysis. Cultivars showed significant differences in biomass production and CWP in both years. Excalibur teff grass variety had the greatest CWP (418 kg ha^{-1} cm^{-1}) 40 days after planting (DAP) in 2016, and was similar to SS and PM for the rest of the season until 58 DAP. Pearl millet had the greatest overall CWP (443 kg ha^{-1} cm^{-1}) at 44 DAP. In 2017, sorghum sudangrass had significantly greater CWP than teff grass and pearl millet throughout most of the season. Among the teff varieties, Haymore had the greatest CWP (239 kg ha^{-1} cm^{-1}) when harvested 10 days after boot stage (DAB). Crude protein values of teff grass varieties ranged from 9.3% to 21.3%, depending on the harvest date and year. Teff grass showed equivalent or greater nitrogen use efficiency (27.8 – 88.8 kg biomass kg^{-1} N applied) in our study than previously reported. Teff grass demonstrated potential to provide producers with a fast-growing and competitive forage crop with less overall water use due to a shortened growing season.

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Dedication

To my parents: Craig Davidson and Dr. Janice Unruh Davidson.

Chapter 1 - Literature Review

Origin, distribution, and uses

Teff grass (*Eragrostis tef* [Zucc.] Trotter) entered recorded history around 7000 *BP* in Ethiopia (Murphy, 2007). Today, more than five million farmers grow nearly 3.8 millon tons of teff grain each year in Ethiopia (Girma et al., 2014). *Eragrostis pilosa*, widely believed to be teff grass's closest ancestor (Mengistu and Mekonnen, 2012; Girma et al. 2014; Ingram and Doyle, 2003), gives a picture of what teff grass was like before millennia of human selection altered its genetic makeup. Not having generations of selection, *E. pilosa* disperses its seed upon maturity, making it unsuitable for harvest (Ingram and Doyle, 2003). Teff grass, however, has evolved to keep the spikelet components intact, allowing the grain to be harvested.

In Ethiopia, teff grass is "grown on roughly 3 of the 8 million ha used to cultivate cereals annually", and most of what is produced is consumed in country (Girma et al., 2014). Teff flour is used to make Ethiopian injera, a sourdough flatbread, and accounts for 30% of the caloric intake in the urban areas of Ethiopia (Demeke et al., 2013). Teff grain is also used to produce "Tella" a popular Ethiopian beer. Despite being of such importance to Ethiopian cuisine, teff grain has not become a staple crop of any other country (Lost Crops of Africa, 1996). Teff flour appeals to the gluten-intolerant population as it is gluten free and highly nutritious. Abebe et al. (2007) reported 150 mg of iron per 100 g of whole grain teff. They also reported calcium levels as high as 155 mg per 100 g of whole grain teff. The values for both iron and calcium were significantly higher than other studied cereals such as maize and barley.

Its straw, commonly called stover or fodder, is highly valued for livestock feed in Ethiopia. Many have reported the use of teff grass as a forage in South Africa and Australia (Ingram and Doyle, 2003; Mengistu and Mekonnen, 2012; Lost Crops of Africa, 1996). In Lost

Crops of Africa (1996), the author tells the story of a farmer who had excess teff hay and decided to send it to market in Johannesburg, South Africa. Since many were not familiar with teff hay, it was bought to be used as bedding for race horses, but the horses ended up eating it instead of their feed, which led the owner to buy the rest of the teff hay at the market.

Interest in teff in the U.S. has primarily been as a forage, but teff has also found a niche in the health foods market as well as in the cover crop market (Miller, 2009; Midwest Cover Crops Field Guide, 2014). Pure Seed Testing, a company out of Hubbard, Oregon, has developed interest in teff grass because they “see a lot of potential for a white seeded teff variety that could be used in the high-quality forage market, the alternative grain market, and possibly the cover crop market” (Austin Fricker, Pure Seed Testing, personal communication, 2017). Researchers such as Saylor (2017), Pugh (2016), Norberg et al. (2009), and Newman et al. (2012) have evaluated teff grass both as a grain crop and as a forage crop. Saylor (2017) conducted a feeding study using teff hay as an alternative feed source for dairy cattle and concluded that teff hay can be used “without negatively impacting [dry matter intake] or milk and component production.” A testament to its demand, even here in the United States, Ethiopian restaurant owners have contacted Kansas State in search of farmers who produce teff grain to supply their demand (Dr. Doohong Min, personal communication, 2017).

Biological & agronomic characteristics

Teff grass is one of 5044 grasses that use the Hatch-Slack pathway commonly known as C_4 photosynthesis (Sage, 2016). Less common than C_3 plants, plants that use the C_4 pathway can enhance efficiency by spatially isolating the Rubisco enzyme from the presence of oxygen. In C_3 plants, an inefficient process known as photorespiration occurs when rubisco binds oxygen (Taiz and Zeiger, 2003). Most C_4 plants have "Kranz" anatomy, which stands for "wreath" in German. This was named due to the layer of mesophyll cells that form a "wreath" around the bundle sheath cells where Rubisco is found. This spatial separation allows for the inhibition of oxygen from diffusing into the bundle sheath cells (Taiz and Zeiger, 2003). Thus, as a C_4 plant, teff grass is physiologically better suited for warmer climates and can handle water deficits better than similar C_3 plants.

Teff grass has characteristically small seeds with 100 seeds weighing 0.03-0.05 grams (Bedane et al., 2015). Its inflorescence, or panicle, can be classified into four different types: Very compact, semi-compact, fairly loose, and very loose (Assefa et al., 2015). Establishment of teff grass requires a firm, moist seedbed (Bedane et al., 2015) and should be planted no deeper than 0.9 cm (Evert et al., 2009). Seedlings generally emerge within 3-7 days after planting if conditions are favorable (Evert et al., 2009). While tillage is necessary to produce a clean seedbed, Habtegebrial et al. (2007) demonstrated that similar yields can be obtained with reduced tillage in an oxen plow system. This indicates potential for teff grass to be utilized in no-till systems with proper management. The majority of tillage studies involving teff grass deal with smallholder farmers in Ethiopia who use traditional tillage techniques (Nyssen et al., 2000; Erkossa et al., 2006; Habtegebrial et al., 2007; Temesgen et al., 2009).

After planting, teff grass requires 36-45 days for the panicle to emerge, and it reaches physiological maturity between 83-100 days after planting (Assefa et al., 2001). Teff grass has a shallow, fibrous root system that can penetrate to a depth of 80 cm with 40% of its root weight being in the top 30 cm (Ayele et al., 2001). Teff commonly grows to heights of 40-80 cm (Mengistu and Mekonnen, 2012) and it can produce between 11-42 tillers, depending on the variety (Bedane et al., 2015). In general, the thin stems and heavy panicles of teff grass lends itself to lodging: Nitrogen (N) applications over 60 kg ha^{-1} and high seeding rates have been shown to increase lodging (Pass and Asseng, 2018). Teff grass has shown responses to both nitrogen and phosphorus fertilizer applications. Specifically, dry matter (DM) production was found to increase 29.3 kg for every kg of nitrogen applied (Habtegebrial et al., 2007). Mamo et al. (1996) demonstrated that P "application significantly increased plant height, shoot and root dry weight, and plant P uptake of all tef varieties." Recommended N application rates range from 40-100 kg N ha^{-1} per season and are often split applied before or at planting, and then after each harvest, if applicable (Habtegebrial et al., 2007; Staniar et al., 2010; Norberg et al., 2009). In Ethiopia, grain yield averaged 1.3 Mg ha^{-1} in 2010/2011, up 33% from 2004/2005 (Demeke and Marcantonio, 2013). Forage yield in the United States has ranged from 5-9 Mg ha^{-1} for a single harvest and from 11-16 Mg ha^{-1} for multiple harvests in a season (Norberg et al., 2009; Miller, 2009). Another common forage, sorghum sudangrass, can produce 12-17 Mg ha^{-1}, or up to 16-21 Mg ha^{-1} if using the photoperiod sensitive cultivar of sorghum sudangrass under irrigated conditions (Bean et al., 2013). Bean et al. (2013) also reported similar values for forage sorghum. Forage pearl millet yields in West Texas and New Mexico can range from 6-10 Mg ha^{-1} per cutting, with up to 3 cuttings being possible (Marsalis et al., 2012).

Nutritive value

Forages have two important parts: its cell contents, and its structural, cell wall contents. Cell contents are composed of highly digestible compounds such as “organic acids, proteins, lipids, starch, and sugars” that can be almost entirely consumed (Collins and Fritz, 2003). The cell wall, however, is composed of strong, fibrous compounds such as cellulose, hemicellulose, lignin, and silica that are difficult to breakdown and consume (Collins and Fritz, 2003). As stems develop and the age of the forage increases, forage quality indicators such as voluntary intake (the amount of DM that an animal will consume from an unlimited supply) and DM digestibility (the amount of DM that can be digested in the rumen) decline (Collins and Fritz, 2003).

In order to determine the point at which a forage producer can maintain quality while maximizing yield, forages are often analyzed at different stages of maturity. One the most widely used systems to analyze the nutritive value of a forage is the detergent analysis system. Neutral detergent solubilizes everything but the cell wall components, or, the neutral detergent fiber (NDF), while acid detergent solubilizes the same fraction that neutral detergent does, plus hemicellulose, leaving behind the acid detergent fiber (ADF). Thus, the difference between ADF and NDF is the hemicellulose concentration, which has been found to be 3-4 times higher in the cell walls of grasses than in the cell walls of legumes (Collins and Fritz, 2003). NDF and ADF have been negatively correlated to voluntary intake and dry matter digestibility, respectively (Collins and Fritz, 2003). Values for NDF, ADF, and crude protein (CP) are commonly reported as a percent of dry matter and vary depending on stage of maturity, forage species, and harvesting conditions (Collins and Fritz, 2003).

Alfalfa, a cool season perennial legume, is one of the most common forages grown in the United States and is often the benchmark to which other forages are compared. For example, the relative feed value (RFV) index was developed using legume hay as a benchmark. In this system, an average quality legume hay would have an RFV of 100. The RFV system uses the negative correlations between ADF and dry matter digestibility (DDM), and between NDF and dry matter intake (DMI) to calculate RFV (Rohweder et al., 1978). Well-cured alfalfa hay harvested at the late bud stage commonly exhibits the following nutritive values: NDF = 32%, ADF = 28%, CP = 26%. In comparison, teff grass (warm season annual) harvested at boot stage has 68% NDF, 36% ADF, and 16% CP.

Staniar et al. (2010) conducted a study feeding teff hay to horses and reported nutritive values at three different stages of maturity. At boot stage: NDF = 68.1, ADF = 35.7, CP = 16.4. At early heading: NDF = 71.1, ADF = 40.2, CP = 10.8. At late heading: NDF = 70.8, ADF = 41.5, CP = 7.5. Norberg et al. (2009) reported average values of 60.1 for NDF, and 39.8 for ADF, and 13.1% crude protein from studies conducted in Oregon. Miller (2009) reported ranges of 53-65 for NDF and 32-38 for ADF. Miller (2009) compared those values to that of Timothy grass (a C_3 grass) that had an NDF range of 53-59 and an ADF range of 32-36. Bean et al. (2013) examined the nutritive values of sorghum sudangrass and reported 4 year means of NDF and ADF as 49.8 and 30.2, respectively. Brunette et al. (2010) reported values for pearl millet silage cut at boot stage to be 63.3 for NDF and 39.1 for ADF.

According to Collins and Fritz (2003), warm-season grasses typically have higher fiber values than cool-season grasses, resulting in lower digestibility. The benefits of using a warm season annual such as teff grass or sorghum sudangrass that has lower quality compared to alfalfa is to still be able to produce biomass in the summer when cool season grasses are struggling. The only problem is to make sure that the summer annual forage is of sufficient quality to be used in competitive forage programs. Saylor (2017) found that feeding dairy cattle a teff-based diet does not inhibit dry matter intake or milk production, despite being a high fiber forage. This was accomplished with the use of concentrates (dry ground corn, soybean meal, and soyhulls) and allowed for a decreased forage requirement overall. This study proved the potential of teff grass to be a serious contender for dairy operations in Kansas. Saylor (2017) also stressed the importance of further research on teff grass to determine the nutritive values and economics of growing teff grass under field conditions.

Crop water use

Water use efficiency (WUE) has been defined as “the amount of biomass produced per unit water used” (Naranyan et al., 2013). Depending on a researcher’s objectives, WUE can be measured on many different scales with many different variables. For example, Sinclair et al. (1984) demonstrated three possible scales for biomass (total crop biomass, grain biomass, or carbon dioxide assimilation) and three scales for water consumption (transpiration, evapotranspiration, total water input to the system). Regardless of the scale, the foundation of water use efficiency goes back to a unit of something produced per unit of water used. For producers in Kansas, water use efficiency is generally on a field scale and is often defined as how much grain or biomass they can produce for each inch of water used by the crop system. Adding to the importance of WUE for those producers, portions of the Ogallala aquifer in western Kansas have been declining as a result of “substantial groundwater withdrawals” since the 1960s (Whittemore et al., 2015). In an effort to stabilize water levels of the aquifer, various groundwater management districts have implemented “Local Enhanced Management Areas” (LEMAs) in which irrigators adopt either voluntary or mandatory reductions in the amount of water they pump from the ground. Liebsch (2017) modeled several scenarios of a proposed LEMA in western Kansas and found in one scenario that “utilizing less water-intensive crops” can lead to economic gains without reducing irrigated acreage. As of February 2018, there are two active LEMAs in Kansas that could benefit from utilizing water efficient crops.

The water use and/or water requirement of teff grass is largely understudied. Researchers in Ethiopia have examined the WUE teff grass using FAO’s AquaCrop model (Araya et al., 2010). Using transpiration estimates from the AquaCrop model, a biomass based WUE (kg biomass/mm transpiration) was calculated and ranged from 12.5-27.3 kg mm^{-1} (Araya et al., 2010; Paff and Asseng, 2018). In their review of teff grass physiology, (Paff and Asseng, 2018) also stated “There is limited published information available on the water use efficiency of tef” beyond a model or greenhouse study. Thus, an experiment determining the water use of teff grass under field conditions would benefit many farmers and researchers. The water balance method is commonly used to determine the water use of a crop.

A field scale water balance generally focuses on the rooting zone of a soil profile since crops access water through their roots. Hillel (2004) presented the following soil water balance equation: $\Delta S + \Delta V = (P + I + U) - (R + D + E + T_r)$ where ΔS is the change in stored soil water, ΔV is the amount of water incorporated in plant biomass, P is precipitation, I is irrigation, U is upward capillary flow into the root zone, R is runoff, D is drainage out of the profile, E is evaporation from the soil surface, and T_r is transpiration by plants. This equation can be rearranged and simplified to determine evapotranspiration (ET): $T_r = (P + I) - R - D - \Delta S$. Evapotranspiration is a combined measurement of transpiration from plants and evaporation from the soil from a unit area. This term is necessitated from the difficulties that arise in distinguishing one from the other during a cropping season. Once a crop has grown enough to shade the soil surface below it (canopy closure), evaporation generally becomes minimal and transpiration becomes the dominant pathway of crop water use. Until an adequate canopy is formed by a crop, evaporative losses of water from the soil surface are likely higher than transpiration.

Evapotranspiration is a component of crop water use, which “. . . refers to ET plus losses by runoff and internal drainage from the soil profile” (Stone and Schlegel, 2006). Crop water use estimation that refers to ET plus losses to drainage and runoff has been used for crops such as corn (Schlegel et al., 2018), winter wheat (Aiken et al. 2013), grain sorghum (Narayanan et al, 2013), and cover crops (Kuykendall, 2015). Schlegel et al. (2018) used crop water use (calculated as the sum of soil water depletion plus precipitation) to determine crop water productivity, which was defined as grain yield / crop water use, and is analogous to Narayanan's (2013) definition of biomass based water use efficiency. Since calculations of crop water use often include runoff and drainage, those variables are often assumed to be negligible unless corrections are made. If no corrections are made, it is important to examine the environment in which these assumptions are being made. For example, Khan (1996) determined Wilcox drainage equations for three soils in western Kansas (Keith, Richfield, and Ulysses silt loams) and for a Eudora silt loam (likely a Eudora-Bismarckgrove silt loam today) in eastern Kansas near Manhattan. He found that the equations worked well for the uniform western Kansas soils until the profile reached a certain wetness. The highly variable Eudora silt loam produced equations that could only be used on the same site where they were calculated. Therefore, if the soil profile is uniform and relatively dry, which common in western Kansas, it is reasonable to assume that drainage is negligible. But, if the soil is highly variable in terms of texture, or wet, drainage needs to be considered.

Canopy Formation

Of the 1.3 kW m^{-2} of solar radiation that reaches the earth annually, only 5% of it is converted into useable carbohydrates. (Taiz and Zeiger, 2006). Sixty percent of solar radiation is not usable by plants (nonadsorbed wavelengths), 8% is either reflected or transmitted, another 8% is dissipated as heat, and 19 % is used in metabolism (Taiz and Zeiger, 2006). The wavelength of light in the visible spectrum ranges from 400-700 nm, and is considered to be photosynthetically active radiation (PAR). In terms of agronomy, leaf area index (LAI) is a measurement of the leaf area of a crop covering a unit area. Hay and Porter (2006) suggested that an LAI of three to five is required to harness more than 90% of PAR. Leaf area index is dependent upon many factors, including temperature, nutrient availability, and plant density (Hay and Porter, 2006). Narayanan (2011) stated "Dry matter production increases with LAI and reaches maximum at optimum LAI, beyond which yield does not increase." Since dry matter production increases as LAI increases, the sooner a crop can close its canopy, the sooner that crop can reach optimum yield. The benefits of a closed canopy include, but are not limited to, reduced evaporation from the soil surface and increased photosynthetic capacity. Reduced evaporation from the soil surface aids in water retention. Increasing photosynthetic capacity earlier in the season can allow for faster rates of biomass accumulation, if conditions are right. Although teff grass has been said to close its canopy rather quickly due to a high tillering rate (Paff and Asseng, 2018), canopy formation indices such as LAI and radiation use efficiency have not been determined for teff grass. In the studies mentioned earlier, the AquaCrop model uses parameters such as canopy development and senescence and leaf expansion growth to estimate ground cover from the canopy, rather than leaf area index (Paff and Asseng, 2018). Measuring the actual LAI of teff grass would allow for a better, more quantitative analysis of its canopy formation characteristics.

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Chapter 2 - Evaluating Teff Grass as a Summer Forage

Abstract

Finding a high-value forage crop with limited water requirements to produce livestock feed is becoming increasingly important as producers adapt to restricted water supply conditions. Our objectives were to determine the forage yield, nutritive values, and crop water productivity (CWP) of teff grass (*Eragrostis tef* [Zucc.] Trotter) under field conditions when compared to sorghum sudangrass (SS, *S. x drummondii*[(Nees ex. Steud.) Millsp. & Chase]) and pearl millet (PM, *P. glaucum* [L.]R.Br.). Crop water productivity was determined by dividing above-ground biomass by crop water use. Crop water use was determined by the summation of soil water depletion, precipitation, and irrigation. Yield was determined by quadrat area clippings of above-ground biomass. Nutritive value was determined using wet chemical analysis. Cultivars showed significant differences in biomass production and CWP in both years. Excalibur teff grass variety had the greatest CWP (418 kg ha^{-1} cm^{-1}) 40 days after planting (DAP) in 2016, and was similar to SS and PM for the rest of the season until 58 DAP. Pearl millet had the greatest overall CWP (443 kg ha^{-1} cm^{-1}) at 44 DAP. In 2017, sorghum sudangrass had significantly greater CWP than teff grass and pearl millet throughout most of the season. Among the teff varieties, Haymore had the greatest CWP (239 kg ha^{-1} cm^{-1}) when harvested 10 days after boot stage (DAB). Crude protein values of teff grass varieties ranged from 9.3% to 21.3%, depending on the harvest date and year. Teff grass showed equivalent or greater nitrogen use efficiency (27.8 – 88.8 kg biomass kg^{-1} N applied) in our study than previously reported. Teff grass demonstrated potential to provide producers with a fast-growing and competitive forage crop with less overall water use due to a shortened growing season.

Key words

Teff, *Eragrostis tef*, forage quality, crop water use, nutritive value.

Introduction

Finding a high-value forage crop with limited water requirements to produce livestock feed can provide cropping alternatives to producers adapting to restricted water supplies (Saseendran et al., 2013). In Western Kansas, groundwater levels have been declining as a result of "substantial groundwater withdrawals" since the 1960s (Whittemore et al., 2015). In an effort to stabilize water levels of the high plains aquifer, some groundwater management districts have implemented "Local Enhanced Management Areas" (LEMAs) in which irrigators reduce the amount of water they pump from the ground. Liebsch (2017) modeled several scenarios of a proposed LEMA in western Kansas and found in one scenario that "utilizing less water-intensive crops" can lead to economic gains without reducing irrigated acreage. Therefore, evaluating high-value crops with reduced water requirements can provide management alternatives for producers, especially for those participating in water conservation practices.

A crop that may be able to meet the needs of some growers in western Kansas is teff grass (*Eragrostis tef* [Zucc.] Trotter). The staple crop of Ethiopia, teff is commonly known for its excellent nutritional profile that has attracted a world market for teff as a health food. In the US, however, research has primarily focused on its use as a forage. Researchers such as Saylor (2017), Pugh (2016), Norberg et al. (2009), and Newman et al. (2012) have evaluated teff grass both as a grain crop and as a forage crop. Forage yield in the United States has ranged from 5-9 Mg ha^{-1} for a single harvest and from 11-16 Mg ha^{-1} for multiple harvests in a season (Norberg et al., 2009; Miller, 2009). As with most grass forages, the first cutting generally occurs at late boot stage, just before the panicle emerges from the stem. According to Miller (2009), the nutritive value of teff grass is similar to timothy grass, which is considered to be of high quality for a grass forage. Norberg et al. (2009) reported average values of 60.1 for NDF, and 39.8 for ADF, and 13.1% crude protein from studies conducted in Oregon. Miller (2009) reported ranges of 53-65 for NDF and 32-38 for ADF. Values for teff grass yield and nutritive values are quite variable and often depend on the location. Bean et al. (2013) examined the nutritive values of sorghum sudangrass and reported 4 year means of NDF and ADF as 49.8 and 30.2, respectively. Brunette et al. (2010) reported values for pearl millet silage cut at boot stage to be 63.3 for NDF and 39.1 for ADF.

The water use of teff grass has not been determined in the United States. Norberg et al (2009) stated that a teff crop will use 10-25 cm of water, depending on the location. In order to meet the needs of producers in Kansas who have limitations on water supply, knowledge of water requirements, crop productivity and nutritive value of teff grass can support farm crop selection and water management. Therefore, our objectives were to determine the forage yield, nutritive values, and crop water productivity of teff grass under field conditions when compared to sorghum sudangrass (*S. x drummondii*[(Nees ex. Steud.) Millsp. & Chase]) and pearl millet (*P. glaucum* [L.]R.Br.).

Methods & Materials

Crop Culture

Field sites were established at Kansas State University's Northwest Research-Extension Center in Colby, KS (39°23'36.3"N 101°03'47.7"W) in 2016 and 2017. The plots were established on a Keith silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustolls) in 2016 and on a Richfield silt loam (fine, smectic, mesic Aridic Argiustolls) in 2017. Previous crops for the 2016 and 2017 locations were maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.), respectively. In both years, tillage included passes with a field cultivator and a cultipacker to prepare a firm seedbed. Four commonly available teff varieties, along with sorghum sudangrass and pearl millet, were planted with a drill (Model 1005NT, Great Plains Manufacturing, Salina, KS) with 19 cm row spacing on 8 June in 2016 and 31 May in 2017 in 9.1 m x 6.1 m plots. Sorghum sudangrass and pearl millet were chosen for comparisons due to their popularity as a summer annual forage. In 2016, all cultivars were planted at rates of 11.2 kg ha^{-1}. In 2017, the rates of SS and PM were raised to 22.4 kg ha^{-1} achieve better stands. Areas of poor emergence were reseeded by hand to ensure adequate crop stands. Teff grass was sown no deeper than 1.5 cm, whereas sorghum sudangrass and pearl millet were sown no deeper than 3 cm.

The experiment was designed as a split plot in a randomized complete block with four blocks as replicates. The whole plot effect was cultivar and the split plot effect was the sampling date. Fertilizer applications included 68.4 kg N ha^{-1} as 32-0-0 and 33.6 kg P ha^{-1} as 10-34-0 in both years. Weed management in 2016 included one application of dicamba (3,6-Dichloro-2-methoxybenzoic acid, 0.44 L ha^{-1}) and 2,4-D-LV6 ((2-ethylhexyl ester of 2,4-Dichlorophenoxy)acetic acid, 0.44 L ha^{-1}) and another application of 2,4-D-LV6 ((2-ethylhexyl ester of 2,4-Dichlorophenoxy) acetic acid, 1.17 L ha^{-1}). In 2017, one application of 2,4-D-LV6

((2-ethylhexyl ester of 2,4-Dichlorophenoxy)acetic acid, 0.73 L ha^{-1}) was made. In both years, hand hoeing was required to maintain weed-free plots. Plots were irrigated (50.8 mm in 2016, 30.5 mm in 2017) after planting to aid emergence in both years. Apart from that, no irrigation was applied during the 2016 and 2017 growing seasons.

Biomass Production

Aboveground biomass (AGB) was measured by harvesting plants within a 0.76 x 0.76 m quadrat. In 2016, harvest began on all plots once the majority of teff grass plots had reached late boot stage. All plots were harvested on the same day every 4-5 days from 40-58 days after planting (DAP). In 2017, each plot was harvested once it reached late boot stage. Teff grass varieties were harvested from 41-63 DAP, whereas sorghum sudangrass and forage pearl millet were harvested from 63-82 DAP. In order to compare cultivars, 2017 data are examined by days after boot stage (DAB), with the initial harvest being zero DAB. Dry matter yield was determined after samples were dried to a constant weight at 50°C. Stage of development was recorded at each biomass sampling.

Nutritive Values

Dried biomass samples were ground to pass through a 2mm sieve using a Model 4 Wiley mill (Thomas Scientific, Swedesboro, NJ). Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were analyzed via wet chemical analysis in an Ankom 200 fiber analyzer (Ankom Technology, Macedon, NY). Total nitrogen (%N) was measured using a LECO CN-2000 combustion analyzer (LECO Corp. St. Joseph, MI) by the Kansas State University Soil Testing Lab. Crude protein was then calculated from total %N by multiplying by 6.25. Relative feed value (RFV) was calculated following the method of Rohweder et al. (1978) as

$$RFV = (DDM \times DMI) / 1.29$$

where DDM = dry matter digestibility and DMI = voluntary dry matter intake.

The following equations were used to calculate DDM and DMI

DDM = 88.9 – (0.779 x ADF)

DMI = 120 / NDF

Soil Water Measurements & Calculations

Stored soil water was measured using neutron thermalization (503DR Hydroprobe, CPN International, Concord, CA) with a count duration of 18 s. After crop emergence, aluminum access tubes (6061-T6 aluminum, 5-cm O.D, 0.128-cm wall thickness) were installed to a depth of 290 cm using a custom hydraulic probe. The tubes were driven into place using a slide hammer until fifteen centimeters of the tube remained above the soil surface. Depths of measurement using the neutron probe (Campbell Pacific Nuclear, 503 Hydroprobe) were from 0.3-2.7 m at 0.3-m increments. Thus, soil moisture was measured from 0.15-2.85 m at 0.3 m increments, assuming each measurement recorded moisture from a 30.48 cm sphere. Neutron counts were then converted into volumetric water content (θ, $m^3\ m^{-3}$) using a known calibration curve for the area ($\theta = 22.2685 * CR - 5.27$) where CR is the ‘count ratio’. To calculate an equivalent depth of soil water, the sum of each reading of a soil profile was multiplied by 304.8 mm to be converted into millimeters and by 0.01 to convert the percentage into a fraction. Cumulative water use (CWU) was calculated using the soil water balance (CWU= sum of soil water depletion + precipitation + irrigation [if applied]). No corrections were made for drainage or evaporation. In 2016, berms were installed around each plot to restrict runoff using a “ditcher”; a type of row cultivator. Berms were not installed in 2017 because of miscommunication. Crop water productivity (CWP) was determined by dividing above-ground biomass by crop water use (mm).

2016 Measurements & Calculations

Soil water depletion was calculated for five different sampling periods: 15-40 DAP, 15-44 DAP, 15-48 DAP, 15-54 DAP, and 15-58 DAP, all in relation to biomass sampling. For the first time period, 15-40 DAP, soil water depletion was calculated only to depth of 1.2 m due to irregular measurements from the first sampling at 15 DAP. It is reasonable to assume that crop roots were not extracting water below 1.2 m at 15 DAP. For the rest of the intervals, soil water depletion was calculated to a depth of 2.4 m to ensure that all zones of root water uptake were accounted for.

2017 Measurements & Calculations

Soil water depletion was calculated in relation to biomass sampling for each individual plot in 2017, similar to that in 2016. The field site had three plots where readings were not taken at a particular depth (either 2.1 or 2.4 m). In order to account for those missing values, a value measured four to five days before or after that date was used, assuming a negligible change in stored soil water from drainage. This assumption is based on research conducted by Dr. Akhter Khan who determined Wilcox drainage equations for Keith and Richfield silt loam soils in western Kansas. Soil water depletion was not calculated for measurements that indicated a substantial increase in stored soil water. Instead, an average of soil water depletion from the rest of the plots was used. On 13 July, only four plots were sampled, and each plot indicated a substantial recharge. To compensate for this, a ratio of CWU/KIS_ET calculated for a corn crop for the corresponding interval (06/30/17-07/13/17) was applied. Keep it simple corn irrigation software (KISCORN) was developed by Freddie Lamm (KSU, NWREC, Colby, KS www.ksre.k-state.edu/irrigate/software/kisuse99.html) and estimates ET for a corn crop by multiplying established crop coefficients (Kc) by reference evapotranspiration (ETr). Therefore, the estimates of CWU from 06/30/17 - 07/13/17 are averages of the ratio of CWU/KIS_ET from two dates before and after 07/13/17 (07/11/17, 07/17/17) multiplied by the KIS_ET value from 06/30/17-07/13/17.

Canopy Formation

Leaf area index (LAI) was measured using a LI-COR LAI-2000 plant canopy analyzer (LiCor, Lincoln, NE). In 2016, measurements were taken on 29 and 37 DAP and then every 4-5 days following the start of biomass sampling. In 2017, measurements were taken on days that biomass was sampled. Measurements were taken prior to 9:00 a.m. CST while the sun was at low angles. During sampling, the sensor was shaded from direct sunlight to ensure that only diffuse light was being measured. Canopy transmittance, the amount of light passing through the canopy, was measured from three representative sets of one-above canopy reading, and four below-canopy readings. If canopy transmittance is high, leaf area index will be low, since light is able to pass through the canopy. Likewise, if canopy transmittance is low, that means leaf area is higher and is blocking light from being transmitted through the canopy.

Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) was calculated by dividing biomass by the nitrogen application rate of 68.4 kg ha^{-1}.

Statistical Analyses

Analysis of variance was performed using the GLIMMIX procedure in SAS (SAS Institute, version 9.4, 2012) for biomass, cumulative water use, and forage quality indicators at all measurement dates separately. Biomass data were transformed with a log transformation for analysis and then back-transformed for use in tables and figures. Means were separated using the Bonferroni correction in SAS with an alpha value of 0.05. Entry (cultivar) and harvest date (either DAP or DAB) were treated as fixed effects, and replication was treated as a random effect. Regression analysis for the creation of figures 2.2-2.10 was done in Graphpad Prism 7. A linear or quadratic model was chosen depending on which model produced higher R^2 values.

Results and Discussion

Environmental Conditions

The growing seasons extended from planting to 58 and 82 DAP in 2016 and 2017, respectively (Figure 2.1). Total precipitation for each growing season was 109 mm in 2016, and 188 mm in 2017 (Figure 2.1), both below the 30-yr average for the respective time interval. Average maximum/minimum air temperatures for each growing season were 40/16 °C in 2016 and 33/18 °C in 2017 (Figure 2.1). Overall, 2016 was warmer and drier than average, whereas 2017 received more precipitation than average and had average temperatures. No disease or pest (other than weeds) was observed in either year.

Crop Development

Crops emerged six DAP in 2016 and nine DAP in 2017. This is within the range of teff emergence that Paff and Asseng (2018) reported in their review of teff grass physiology. In 2017, one pearl millet plot was terminated due to poor establishment and growth. All teff varieties reached the late boot stage 41-48 DAP in 2016, and 41-43 DAP in 2017. Sorghum sudangrass and pearl millet reached the late boot stage by 72 and 58 DAP, respectively, in 2016, and by 63 DAP in 2017.

Biomass Production

Cultivars differed in seasonal quantities of biomass productivity in both years (Table 2.11). In 2016, there were two sampling dates (44 and 58 DAP) at which all teff varieties were similar (Table 2.2 and Table 2.5). The highest producing teff variety, Excalibur, was similar to sorghum sudangrass in biomass production at every sampling date except for 58 DAP (Table 2.5). Excalibur was similar to pearl millet in biomass production at 40 DAP. In 2017, all teff varieties produced similar biomass at every sampling date except 5 DAB (Table 2.7). Teff variety Excalibur was similar to pearl millet in biomass production at every sampling date (Figure 2.2). Sorghum sudangrass produced significantly more biomass than all other cultivars at every sampling date (Figure 2.2). Teff grass biomass production was generally similar to the values reported by Norberg et al. (2009) for a single harvest in a season, as the lowest value reported was 4.7 Mg ha^{-1}. However, when harvested multiple times within a season, teff grass can yield 9-15 Mg ha^{-1} (Miller, 2009). Sorghum sudangrass produced 3.0-7.6 Mg ha^{-1} in 2016 and 7.7-10.7 Mg ha^{-1} in 2017. These results are lower than the 12-17 Mg ha^{-1} reported by Bean et al. (2013) who examined sorghum forages under irrigated conditions in West Texas. Pearl millet produced nearly the same amount of biomass in 2017 as in 2016 despite having 24 an additional days to grow. With the exception of pearl millet, biomass production for teff grass and SS was greater in 2017 than in 2016, which is most likely due to greater rainfall during the 2017 growing season.

There was one date at which every cultivar was harvested in 2017. At 63 DAP, teff grass was harvested for the fifth and final time, while sorghum sudangrass and pearl millet were at the boot stage. When compared at 63 DAP in 2017, teff grass variety Excalibur had similar biomass production as sorghum sudangrass and pearl millet (Table 2.20). Every teff grass variety was similar in biomass production to pearl millet at 63 DAP.

Crop Water Use & Productivity

Cumulative crop water use increased linearly throughout the season (Figure 2.3) and showed no differences ($P > 0.05$) among cultivars in 2016 (Table 2.12). Average CWU amongst teff varieties at the last sampling date was 204 mm in 2016 (Table 2.5). Crop water productivity showed significant differences ($P < 0.001$) in 2016 (Table 2.13). A second-order regression model was used to regress biomass on CWU (Figure 2.10). Excalibur teff grass variety had the greatest CWP (420 kg ha^{-1} cm^{-1}) 40 DAP (Table 2.1) in 2016 , and was similar to sorghum sudangrass and pearl millet for the rest of the season until 58 DAP (Table 2.5). Pearl millet had the greatest overall CWP of 443 kg ha^{-1} cm^{-1} at 44 DAP (Table 2.2), which is higher than what has been reported for corn (24.2 kg ha^{-1} mm^{-1}) and foxtail millet (33.0 kg ha^{-1} mm^{-1}) (Nielsen et al., 2006).

Since the calculations of CWU of sorghum sudangrass and pearl millet are 24 days longer than the calculations of CWU for teff grass, comparisons will not be made across species in 2017. Therefore, average CWU amongst teff varieties at the last sampling date was 267 mm in 2017 (Table 2.10). Teff grass variety haymore had the greatest CWP (239 kg ha^{-1} cm^{-1}) amongst teff varieties in 2017 at 15 DAB (Table 2.9). In 2017, there was one sampling date (63 DAP) at which all cultivars were harvested. At 63 DAP, CWU showed no differences (Table 2.20), but two teff grass varieties, Corvallis and Excalibur, showed similar CWP compared to sorghum sudangrass and pearl millet in 2017 (Table 2.20). Sorghum sudangrass and pearl millet showed no differences in CWU throughout the season. Sorghum sudangrass had greater CWP than pearl millet at every sampling date except 0 DAB and 15 DAB.

Norberg et al. (2009) stated that typical water use for a teff crop was between 100-250 mm. This is consistent with our CWU findings of 90 mm at the lowest (Table 2.1) and 287 mm at the highest (Table 2.10). Crop water use was generally greater in 2017 than in 2016, likely due to the increased biomass production and increased rainfall. In order to evaluate our assumption of negligible drainage in the calculations of CWU, drainage was calculated using the equations developed by Khan (1996) for Keith and Richfield silt loam soils. Average drainage during the growing season was found to be 0.0063 mm d^{-1} in 2016 and 0.0091 mm d^{-1} in 2017, validating our assumption of negligible drainage.

Nutritive Values

Crude Protein

Cultivars showed significant differences ($P < 0.0001$) in CP values in 2016 (Table 2.15), with the highest percentages occurring at the first harvest (40 DAP) for teff grass variety Corvallis (21.3%) and PM (21.8%) (Table 2.1). Cultivars showed no differences ($P > 0.05$) in CP in 2017 (Table 2.15) and were lower overall compared to 2016 (Figure 2.5). Teff grass variety Corvallis had the highest level of protein (17.1%) in 2017 at zero DAB (Table 2.6). As expected, crude protein content generally decreased across harvests in both years, with some cultivars plateauing around 11-12% late in the 2017 season (Figure 2.5). As shown in the R^2 values in Figure 2.5, SS and PM exhibited significant variation in crude protein in 2017. The reason for this is unknown. Crude protein content was higher at boot stage in our study in 2016 than was reported by Staniar et al. (2010). In 2017, however, the results were similar. DeBoer et al. (2017) also reported values higher than Staniar et al. (2010) and attributed their higher CP values to mineralization of organic matter from previously applied manure. Crude protein was likely lower in 2017 due to higher yields, as protein content generally decreases as plant fiber increases (Collins and Fritz, 2003). The lowest reported CP value for teff grass from DeBoer et al. (2017) was 16.6%, whereas our study showed a lowest value of 14.2% (Table 2.5) in 2016 and 9.3% (Table 2.9) in 2017. DeBoer et al. (2017) also showed teff grass and SS as having similar mean CP levels across the season. This was generally the case in our study, as at least one variety of teff grass was similar to the CP of SS at every cutting in both years.

Fiber Content

Acid detergent fiber content also varied among cultivars in 2016 ($P < 0.05$) and in 2017 ($P < 0.01$) (Table 2.16). Pearl millet and SS had lower ADF content early in the season (), while the teff varieties were higher early in the season (30 - 33%). Note that the ADF values had significant variation across the season and did not increase linearly as expected (Figure 2.6). Acid detergent fiber values were highest in SS in 2017 for most of the season, whereas teff grass variety Corvallis had the lowest ADF values for most of the season (Figure 2.6). Norberg et al. (2009) reported an average ADF value of 39.9% for teff grass, which is higher than what we found in both years. The numbers were closer to that in 2017, but only reached a maximum of 36.2% (Table 2.8), which was their minimum. In 2016, the maximum ADF value for teff grass in our study was 33.8% (Table 2.3).

Neutral detergent fiber differed among cultivars in 2016 ($P < 0.001$) and in 2017 ($P < 0.05$) (Table 2.17). Neutral detergent fiber values were consistently lower for PM and SS compared to every teff grass variety in 2016 (Figure 2.7). In 2017, however, SS had NDF values more similar to those of the teff grass varieties (Figure 2.7). In both years, NDF values for teff grass were similar to what has been reported in the literature (Miller, 2009; Norberg et al., 2009; DeBoer et al., 2017). Although not significantly different, DeBoer et al. (2017) had lower NDF values that corresponded with their higher CP values. They also reported teff and SS as having similar NDF values which fits their findings of similar CP values.

Bean et al. (2013) showed average CP, ADF, and NDF values of 7.5%, 30.2%, and 49.8%, respectively. Our CP values for SS were greater than 7.5% at every harvest and never went below 10.2 (Table 2.10). This makes sense as SS was harvested while still in the vegetative stage in 2016 and in the boot stage in 2016, while Bean et al. (2013) harvested at the soft dough stage. Our ADF values were similar to Bean et al. (2013) in 2016, but about 5% greater in 2017 (Figure 2.6). Since we had higher CP values, we would expect to have lower, and not greater, ADF values. Brunette et al. (2016) reported mean CP values of 10.4% for a millet silage harvested 65 DAP. Our study found pearl millet CP values to range between 13.0% at the minimum (77 DAP, Table 2.9) to 21.8% at the maximum (Table 2.1), depending on the harvest date. Brunette et al. (2016) also reported values of 63.3% for NDF and 39.1% for ADF. Our NDF values ranged from 53.7% – 62.5%, while our ADF values ranged from 28.2% – 35% (Figure 2.6 and Figure 2.7).

Relative Feed Value

Significant differences ($P < 0.01$) were found among cultivars in both years (Table 2.18). Relative feed value of all teff grass varieties ranged from a minimum of 95 (Table 2.3) to a maximum of 113 (Table 2.1) in 2016. In 2017, RFV ranged from a minimum of 87 (Table 2.10) to a maximum of 105 (Table 2.6). The RFV system was developed so that an average quality legume hay would have a value of 100. Therefore, an alfalfa crop harvested at the bud stage can have an RFV around 150, whereas a brome grass crop harvested at the late vegetative stage can have an RFV around 90 (Dunham, 1998).

Canopy Formation

Leaf area index showed significant differences among cultivars in 2016 ($P < 0.0001$) and 2017 ($P < 0.05$) (Table 2.14). Campbell and Norman (1998) stated that a leaf area index around three will cover the ground well. Based on this statement, pearl millet and every teff variety had a closed canopy (LAI ~ 3) by 40 DAP (Table 2.1, Figure 2.4), but sorghum sudangrass did not achieve canopy closure until 48 DAP in 2016 (Table 2.3), which is likely due to poor sorghum sudangrass stands in 2016. In 2017, only one teff variety (Moxie) had reached canopy closure by the first harvest (Table 2.6). By 5 DAB, every cultivar had a closed canopy (Table 2.7).

Nitrogen Use Efficiency

Cultivars differed in nitrogen use efficiency (NUE) in both years (Table 2.19). In 2016, NUE for teff grass ranged from a minimum of 30.9 kg DM kg^{-1} N at 40 DAP (Table 2.1) to a maximum of 82.5 kg DM kg^{-1} N at 54 DAP (Table 2.4) in 2016 and from 27.8 – 88.8 kg DM kg^{-1} N applied. In 2017, NUE for teff grass ranged from a minimum of 27.8 kg DM kg^{-1} N at zero DAB (Table 2.6) to a maximum of 82.5 kg DM kg^{-1} N at 20 DAB (Table 2.10). Since the nitrogen rate was constant, the trends for NUE (Figure 2.9) will match the trends for biomass (Figure 2.2). At 63 DAP in 2017, teff grass variety Excalibur had similar NUE compared to sorghum sudangrass (Table 2.20). Habtegebrial et al. (2007) found that teff grass can produce 29.3 kg of dry matter (DM) for every kg of nitrogen applied. Our study showed higher NUE overall in both years.

Conclusions

Teff grass can be a competitive summer annual forage in Kansas. In 2016, teff grass variety Excalibur was similar to sorghum sudangrass in biomass production, nutritive value, and crop water productivity. Average crop water use amongst teff grass varieties at the last sampling date was 204 mm in 2016. In 2017, teff variety Excalibur had similar biomass production, nutritive value, and crop water productivity as pearl millet. Average crop water use amongst teff grass varieties at the last sampling date was 267 mm in 2017. In both years, no significant differences in crop water use were found among teff grass varieties, indicating consistency in water use among varieties. Teff grass could excel as a double crop following wheat and prior to fall planting of a subsequent wheat crop. Teff grass could also be grown as a cover crop and/or as an emergency forage. Being able to produce a crop on less than 200 mm of water (single harvest), could be beneficial to producers who have access to sprinkler irrigation, which may be required for crop establishment. Further research into teff grass should include multiple locations in Kansas to give producers a better picture of how teff grass may respond in their environment. Field scale establishment studies such as drilled vs broadcast planting methods could be beneficial in making teff grass a feasible crop for producers in Kansas.

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Figures & Tables

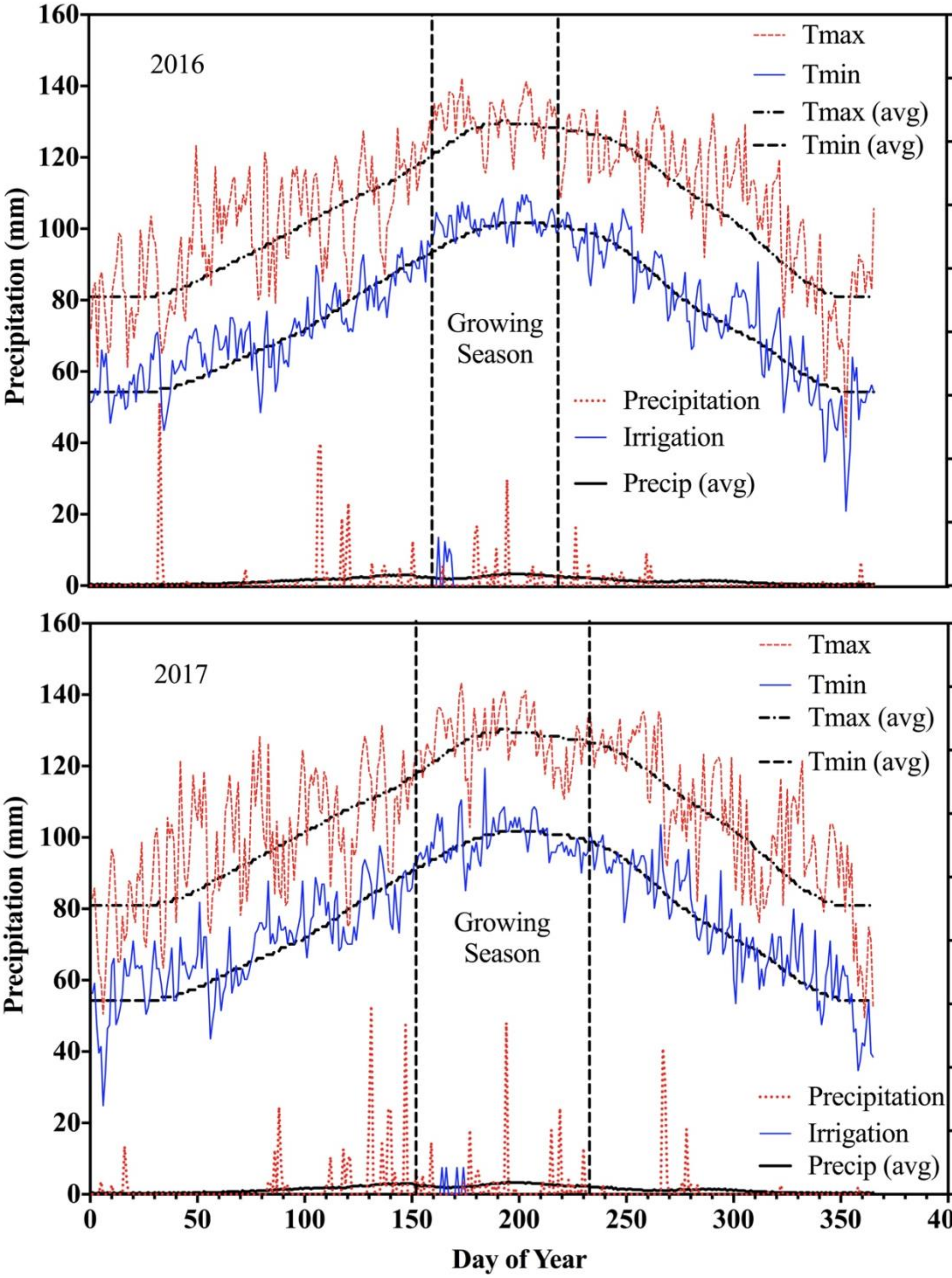

Figure 2.1 - Daily observed maximum and minimum temperatures and precipitation. Obtained from the Northwest Research and Extension Center in Colby, KS.

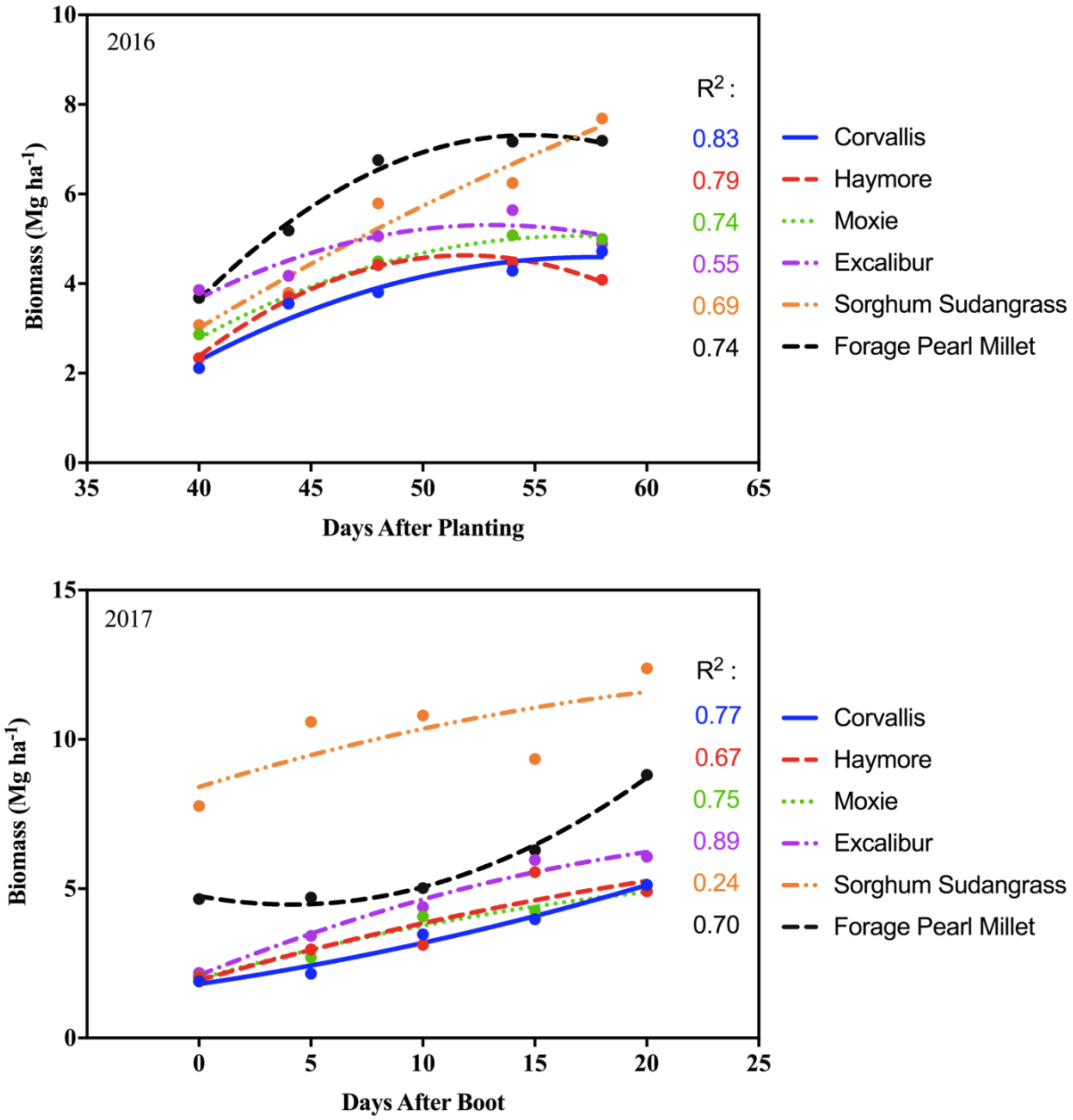

Figure 2.2 – Second-order regression models for above-ground biomass production in 2016 and 2017. For 2017, note that the first sampling date (zero DAB) for SS and PM was 63 days after planting compared to 41 or 43 DAP for teff grass varieties.

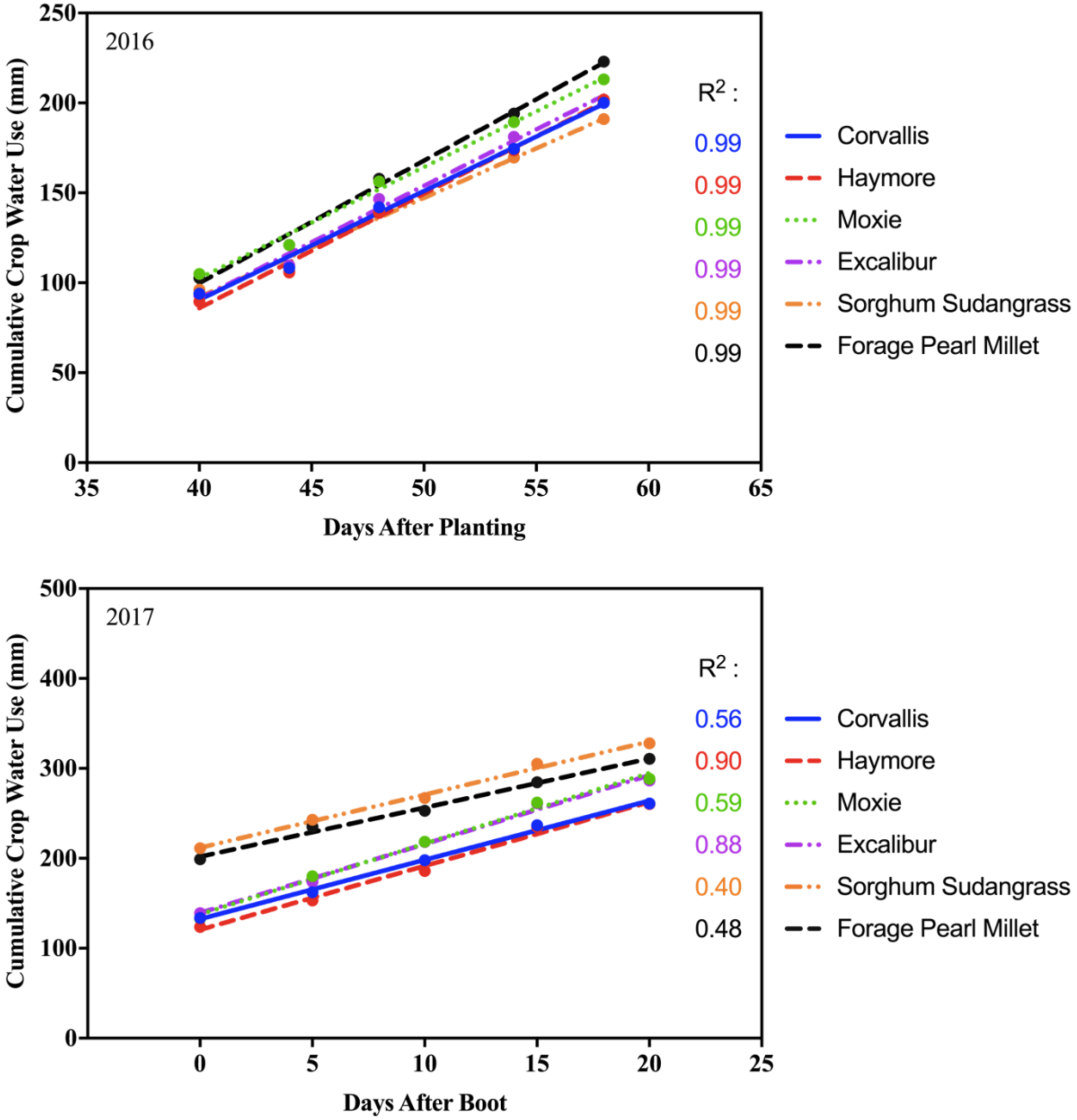

Figure 2.3 – Linear regression models of cumulative crop water use from 2016 and 2017. For 2017, note that the first sampling date (zero DAB) for SS and PM was 63 days after planting compared to 41 or 43 DAP for teff grass varieties.

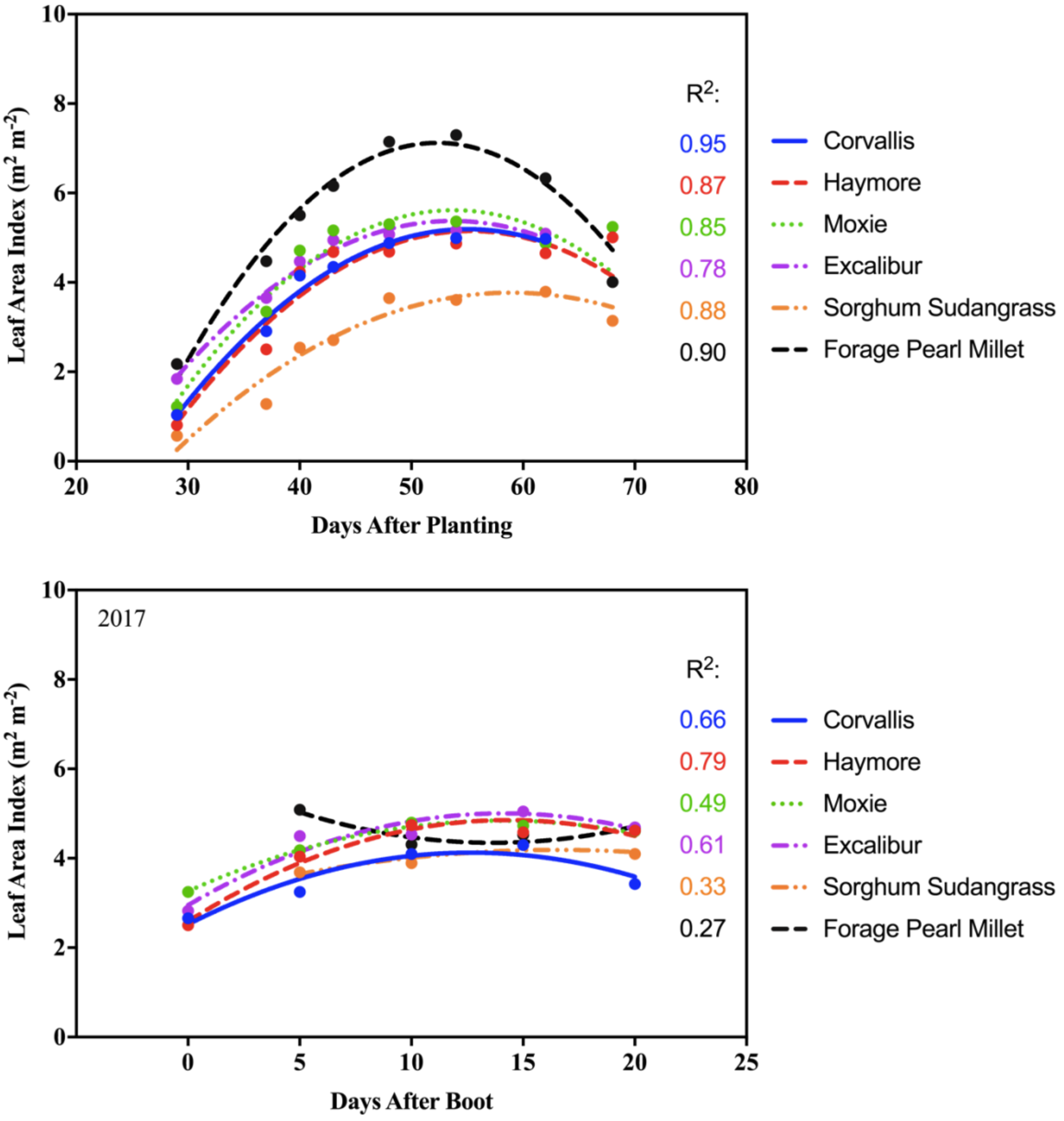

Figure 2.4 – Second-order regression models for leaf area index from 2016 and 2017. In 2017, LAI was only measured on days that biomass was sampled.

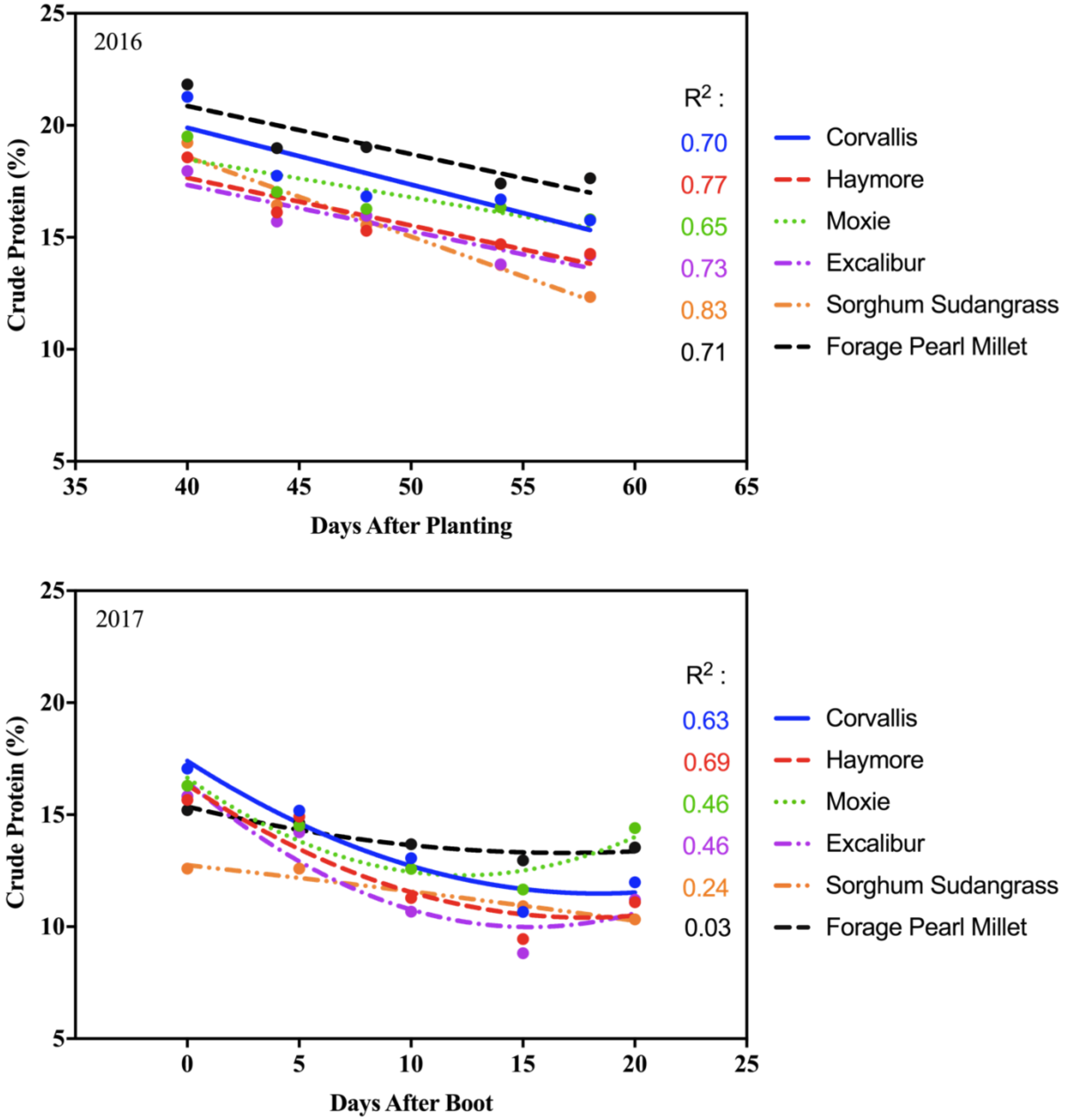

Figure 2.5 – Crude protein from 2016 and 2017. A first order-model was fit for 2016, whereas a second-order model was fit for 2017.

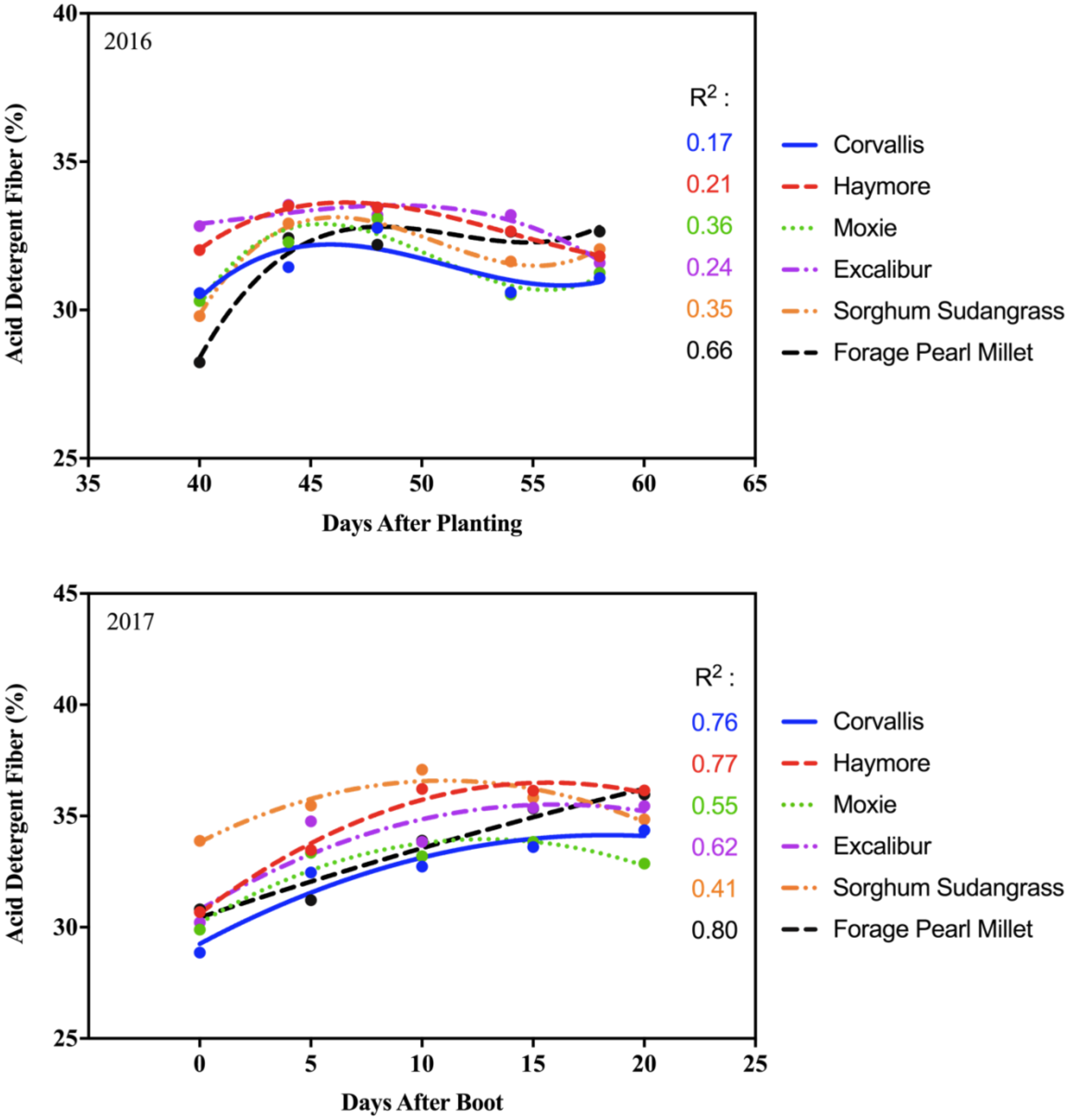

Figure 2.6 – Acid detergent fiber from 2016 and 2017. A third-order model was fit for 2016, and a second-order model was fit for 2017.

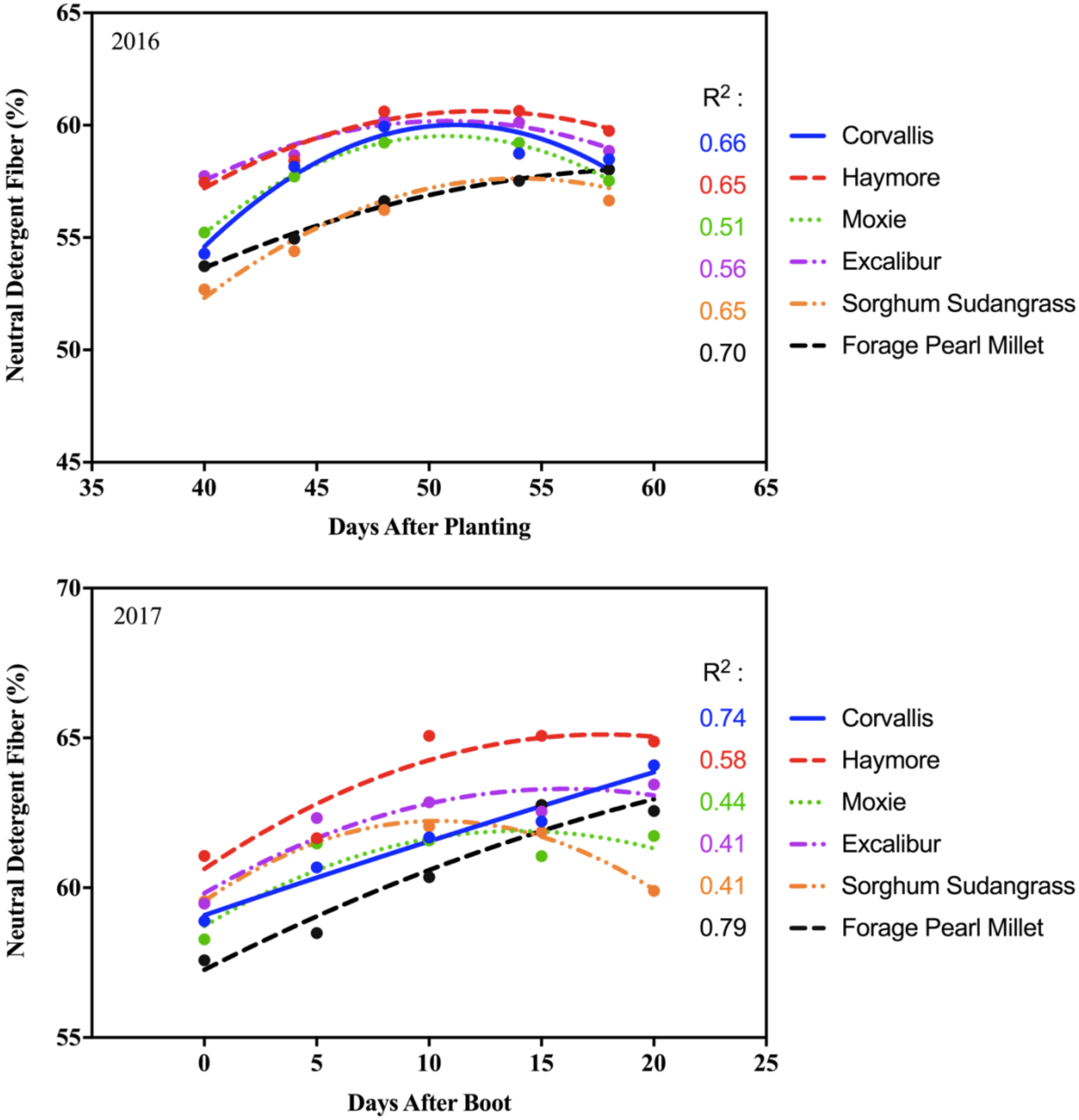

Figure 2.7 – Second-order regression models of neutral detergent fiber from 2016 and 2017.

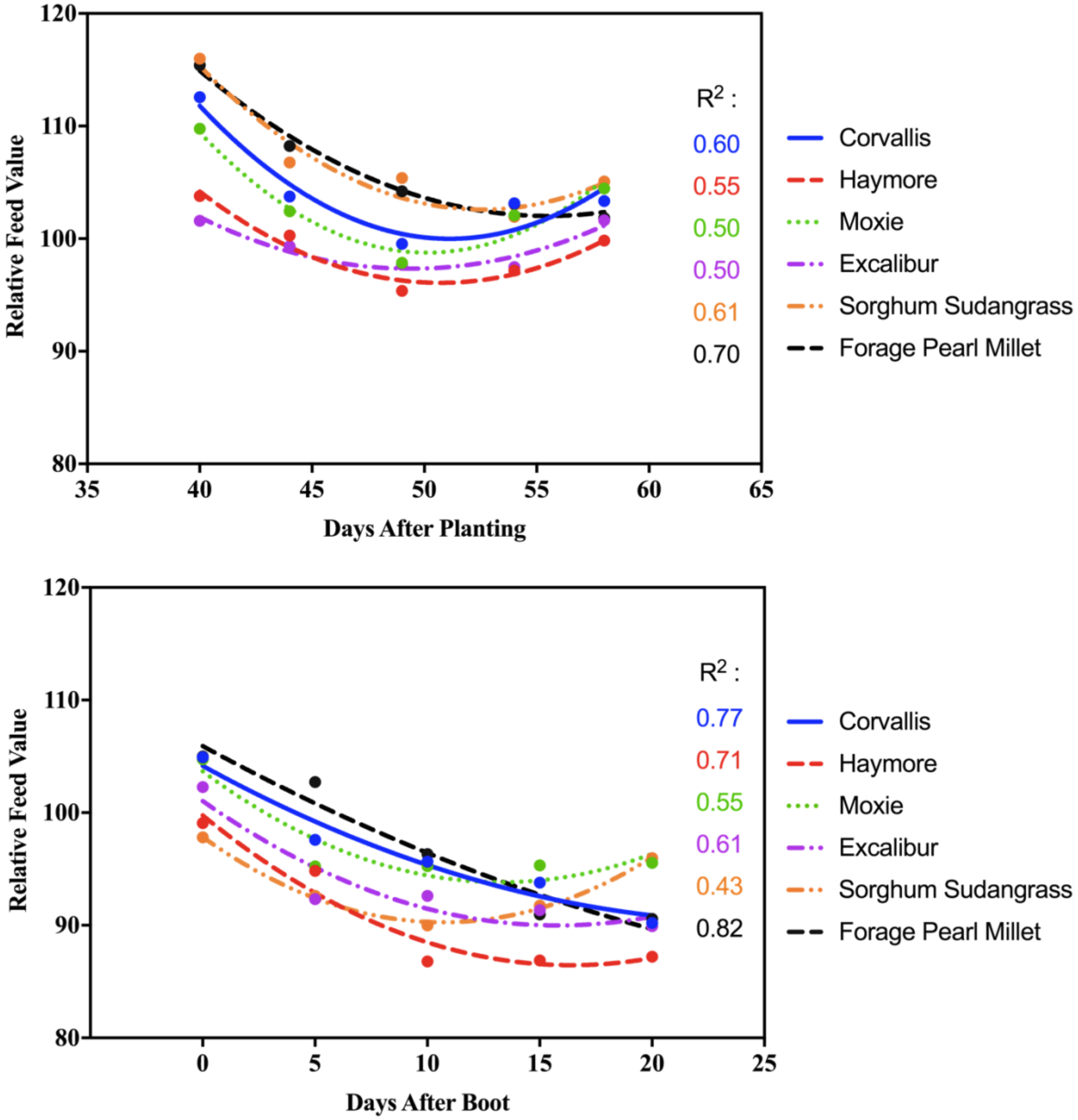

Figure 2.8 – Second-order regression models of relative feed value from 2016 and 2017.

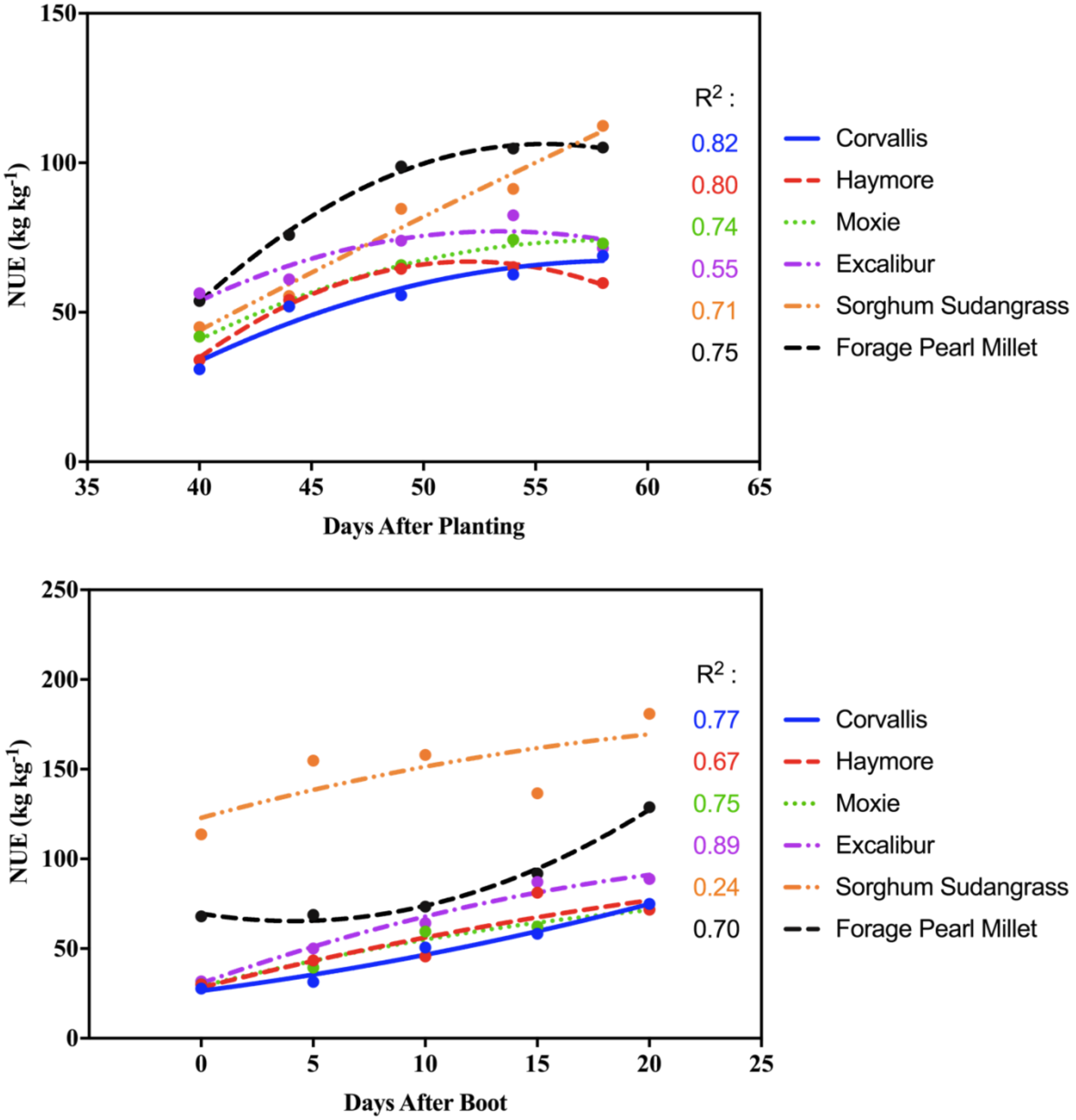

Figure 2.9 – Second-order regression models of nitrogen use efficiency from 2016 and 2017.

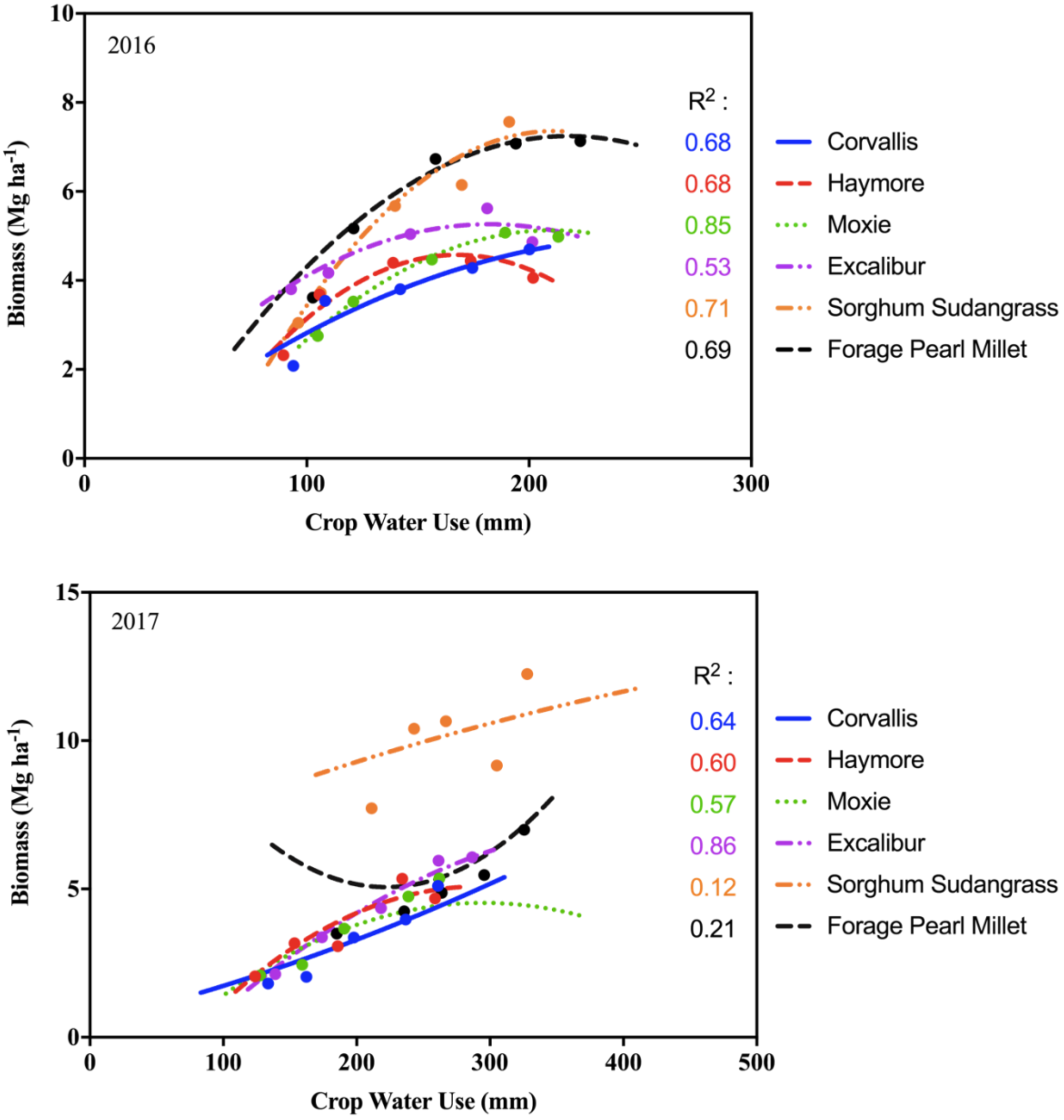

Figure 2.10 – Second-order regression of biomass on crop water use from 2016 and 2017.

Table 2.1 – Forage performance indicators (LSMEANS) at 40 DAP in 2016.

Cultivars	Biomass (Mg ha^{-1})	CWU (mm)	CWP (kg ha^{-1} cm^{-1})	LAI (m^{2} m^{-2})	CP (%)	ADF (%)	NDF (%)	RFV	NUE (kg kg^{-1})
Corvallis	2.1 c	94 a	230 c	4.2 b	21.3 a	30.6 abc	54.3 ab	113 abc	30.9 b
Haymore	2.3 bc	90 a	260 bc	4.2 b	18.6 bc	32.0 ab	57.5 a	104 bc	31.1 ab
Moxie	3.0 abc	105 a	270 bc	4.7 ab	19.5 b	30.3 abc	55.2 ab	110 abc	42.9 ab
Excalibur	3.8 a	93 a	420 a	4.5 b	18.0 c	32.8 a	57.7 a	102 c	56.4 a
SS	3.0 abc	96 a	319 abc	2.5 c	19.2 bc	29.8 bc	52.7 b	116 a	45.0 ab
PM	3.6 ab	103 a	365 ab	5.5 a	21.8 a	28.2 c	53.7 ab	115 ab	53.8 a
Standard Error	1.12	6.7	30.0	0.21	0.35	1.73	0.97	2.34	4.73

*LSMEANS with the same letter are not significantly different according to Bonferroni grouping (α=0.05).

Table 2.2 – Forage performance indicators (LSMEANS) at 44 DAP in 2016.

Cultivars	Biomass (Mg ha^{-1})	CWU (mm)	CWP (kg ha^{-1} cm^{-1})	LAI (m^{2} m^{-2})	CP (%)	ADF (%)	NDF (%)	RFV	NUE (kg kg^{-1})
Corvallis	3.5 b	108 a	331 ab	4.35 b	17.8 ab	31.4 a	58.2 a	104 a	55.4 b
Haymore	3.7 b	106 a	350 ab	4.68 b	16.1 c	33.5 a	58.4 a	100 a	54.1 b
Moxie	3.5 b	121 a	295 b	5.14 ab	17.0 bc	32.3 a	57.7 ab	102 a	51.9 b
Excalibur	4.2 ab	110 a	384 ab	4.95 b	15.7 c	33.5 a	58.7 a	99 a	61.1 ab
SS	3.7 b	106 a	358 ab	2.71 c	16.5 bc	32.9 a	54.4 b	107 a	55.4 b
PM	5.2 a	121 a	443 a	6.16 a	19.0 a	32.4 a	55.0 ab	108 a	75.9 a
Standard Error	1.07	7.1	31.3	0.25	0.33	0.69	0.90	2.74	3.78

*LSMEANS with the same letter are not significantly different according to Bonferroni grouping (α=0.05).

Table 2.3 – Forage performance indicators (LSMEANS) at 48 DAP in 2016.

Cultivars	Biomass (Mg ha^{-1})	CWU (mm)	CWP (kg ha^{-1} cm^{-1})	LAI (m^2 m^{-2})	CP (%)	ADF (%)	NDF (%)	RFV	NUE (kg kg^{-1})
Corvallis	3.8 c	142 a	269 c	4.88 bc	16.9 b	33.8 a	59.9 a	100 ab	55.7 c
Haymore	4.4 bc	139 a	321 bc	4.69 c	15.3 b	33.5 a	60.6 a	95 b	64.5 bc
Moxie	4.5 bc	156 a	287 c	5.31 b	16.3 b	33.1 a	59.2 a	98 b	65.8 bc
Excalibur	5.0 b	147 a	347 abc	5.07 bc	16.0 b	33.2 a	60.2 a	98 b	74.0 abc
SS	5.7 ab	140 a	413 ab	3.65 d	15.6 b	32.8 a	56.2 b	105 a	84.7 ab
PM	6.7 a	158 a	435 a	7.15 a	19.0 a	32.2 a	56.6 b	104 a	98.8 a
Standard Error	1.07	7.9	25.1	0.13	0.41	0.33	0.57	1.18	5.33

*LSMEANS with the same letter are not significantly different according to Bonferroni grouping (α=0.05).

Table 2.4 – Forage performance indicators (LSMEANS) at 54 DAP in 2016.

Cultivars	Biomass (Mg ha^{-1})	CWU (mm)	CWP (kg ha^{-1} cm^{-1})	LAI (m^2 m^{-2})	CP (%)	ADF (%)	NDF (%)	RFV	NUE (kg kg^{-1})
Corvallis	4.3 c	174 a	246 b	4.99 b	16.7 a	30.6 a	58.8 ab	103 a	62.6 c
Haymore	4.4 c	174 a	257 b	4.87 b	14.7 bc	32.7 a	60.6 a	97 a	65.2 bc
Moxie	5.0 bc	189 a	269 b	5.36 b	16.3 ab	30.5 a	59.2 ab	102 a	74.3 bc
Excalibur	5.6 abc	181 a	315 ab	5.17 b	13.8 c	33.2 a	60.1 a	97 a	82.5 abc
SS	6.1 ab	170 a	368 a	3.61 c	13.8 c	31.6 a	58.7 ab	102 a	92.3 ab
PM	7.1 a	194 a	370 a	7.30 a	17.4 a	32.6 a	57.5 b	103 a	105 a
Standard Error	1.07	8.9	30.0	0.17	0.45	0.92	0.53	1.62	5.71

*LSMEANS with the same letter are not significantly different according to Bonferroni grouping (α=0.05).

Table 2.5 – Forage performance indicators (LSMEANS) at 58 DAP in 2016.

Cultivars	Biomass (Mg ha^{-1})	CWU (mm)	CWP (kg ha^{-1} cm^{-1})	LAI (m^{2} m^{-2})	CP (%)	ADF (%)	NDF (%)	RFV	NUE (kg kg^{-1})
Corvallis	4.7 b	200 a	236 bc	NA†	15.8 ab	31.1 a	58.5 a	103 a	68.9 b
Haymore	4.1 b	202 a	203 c	NA	14.2 bc	31.8 a	59.8 a	100 a	59.8 b
Moxie	5.0 b	213 a	234 bc	NA	15.8 ab	31.3 a	57.5 a	104 a	73.0 b
Excalibur	4.9 b	202 a	243 bc	NA	14.2 bc	31.6 a	58.9 a	102 a	71.4 b
SS	7.6 a	191 a	407 a	NA	12.4 c	32.1 a	56.7 a	105 a	112 a
PM	7.1 a	223 a	331 ab	NA	17.6 a	32.6 a	58.0 a	102 a	105 a
Standard Error	1.07	8.3	30.7	NA	0.50	0.61	0.84	2.10	6.66

*LSMEANS with the same letter are not significantly different according to Bonferroni grouping (α=0.05).
†No measurement taken.

Table 2.6 – Forage performance indicators (LSMEANS) at 0 DAB in 2017.

Cultivars	Biomass (Mg ha^{-1})	CWU (mm)	CWP (kg ha^{-1} cm^{-1})	LAI (m^{2} m^{-2})	CP (%)	ADF (%)	NDF (%)	RFV	NUE (kg kg^{-1})
Corvallis	1.8 b	134 b	146 b	2.66 a	17.1 a	28.9 b	58.9 ab	105 a	27.8 c
Haymore	2.1 b	124 b	170 b	2.56 a	15.5 ab	30.9 b	61.7 a	99 a	29.8 c
Moxie	2.1 b	128 b	168 b	3.02 a	16.4 ab	29.7 b	58.6 b	105 a	30.1 c
Excalibur	2.1 b	139 b	157 b	2.83 a	15.8 ab	30.2 b	59.5 ab	102 a	31.8 c
SS	7.7 a	211 a	376 a	NA†	12.6 b	33.9 a	59.5 ab	98 a	114 a
PM	3.5 b	185 ab	228 ab	NA†	15.4 ab	30.8 b	57.7 b	105 a	68.0 b
Standard Error	1.14	16.2§	36.8	0.14‡	1.06§	0.58§	0.72§	1.75§	5.91§

*LSMEANS with the same letter are not significantly different according to Bonferroni grouping (α=0.05).
†No measurement taken.
§Standard error for pearl millet: CWU=18.7, CWP=42.5, CP=1.22, ADF=0.66, NDF=0.84, RFV=2.02, NUE=6.82.
‡Standard error for moxie is 0.17.

Table 2.7 – Forage performance indicators (LSMEANS) at 5 DAB in 2017.

Cultivars	Biomass (Mg ha^{-1})	CWU (mm)	CWP (kg ha^{-1} cm^{-1})	LAI (m^{2} m^{-2})	CP (%)	ADF (%)	NDF (%)	RFV	NUE (kg kg^{-1})
Corvallis	2.0 d	162 b	134 b	3.25 c	15.2 a	32.5 bc	60.7 a	98 ab	31.5 b
Haymore	3.2 bcd	153 b	213 b	3.97 abc	14.4 a	33.9 abc	62.2 a	95 ab	43.4 b
Moxie	2.4 cd	159 b	158 b	4.22 abc	15.1 a	33.1 abc	60.8 a	95 ab	39.3 b
Excalibur	3.4 bc	174 ab	198 b	4.50 ab	14.2 a	34.8 ab	62.3 a	92 b	50.0 b
SS	10.4 a	243 a	441 a	3.69 bc	12.6 a	35.5 a	61.6 a	93 b	155 a
PM	4.2 b	236 a	195 b	4.84 a	14.5 a	31.8 c	59.5 a	103 a	68.8 b
Standard Error	1.13	19.2§	31.6§	0.23§	1.16§	0.55§	0.66§	1.58§	8.56§

*LSMEANS with the same letter are not significantly different according to Bonferroni grouping (α=0.05).

§Standard error for pearl millet: CWU=22.1, CWP=36.4, LAI=0.26, CP=1.34, ADF=0.64, NDF=0.76, RFV=1.82, NUE=9.89.

Table 2.8 – Forage performance indicators (LSMEANS) at 10 DAB in 2017.

Cultivars	Biomass (Mg ha^{-1})	CWU (mm)	CWP (kg ha^{-1} cm^{-1})	LAI (m^{2} m^{-2})	CP (%)	ADF (%)	NDF (%)	RFV	NUE (kg kg^{-1})
Corvallis	3.4 bc	198 a	183 b	4.10 a	13.1 a	32.7 c	61.7 ab	96 a	50.7 b
Haymore	3.1 c	186 a	168 b	4.97 a	10.9 a	36.2 ab	64.6 a	87 b	45.6 b
Moxie	3.7 bc	191 a	198 b	5.01 a	12.4 a	34.2 abc	62.7 ab	95 a	59.5 b
Excalibur	4.4 bc	218 a	202 b	4.53 a	10.7 a	33.6 bc	62.9 ab	93 ab	64.2 b
SS	10.7 a	267 a	423 a	3.89 a	11.3 a	37.1 a	62.0 ab	90 ab	158 a
PM	4.9 b	264 a	197 b	4.03 a	13.5 a	33.5 bc	60.7 b	96 a	74.4 b
Standard Error	1.10	24.1§	35.2§	0.38§	1.50	0.64§	0.54§	1.23§	8.30§

*LSMEANS with the same letter are not significantly different according to Bonferroni grouping (α=0.05).

§Standard error for pearl millet: CWU=27.9, CWP=40.7, LAI=0.44, CP=1.73, ADF=0.74, NDF=0.63, RFV=1.42, NUE=9.58.

Table 2.9 – Forage performance indicators (LSMEANS) at 15 DAB in 2017.

Cultivars	Biomass (Mg ha^{-1})	CWU (mm)	CWP (kg ha^{-1} cm^{-1})	LAI (m^{2} m^{-2})	CP (%)	ADF (%)	NDF (%)	RFV	NUE (kg kg^{-1})
Corvallis	4.0 b	237 a	174 b	4.30 a	10.7 a	33.6 b	62.2 a	94 a	58.2 b
Haymore	5.4 b	234 a	239 ab	4.58 a	9.3 a	36.1 a	64.8 a	87 b	81.2 b
Moxie	4.7 b	239 a	204 ab	4.75 a	10.9 a	34.4 ab	62.1 a	95 a	62.3 b
Excalibur	6.0 b	261 a	229 ab	5.05 a	8.81 a	35.4 ab	62.5 a	91 ab	87.2 b
SS	9.2 a	305 a	323 a	4.30 a	10.9 a	35.8 ab	61.9 a	92 ab	137 a
PM	5.5 b	296 a	198 ab	4.53 a	13.0 a	35.0 ab	62.5 a	91 ab	91.9 b
Standard Error	1.08	24.1§	33.6§	0.19§	1.14§	0.46§	0.62	1.30§	7.93§

*LSMEANS with the same letter are not significantly different according to Bonferroni grouping (α=0.05).

§Standard error for pearl millet: CWU=27.9, CWP=38.8, LAI=0.22, CP=1.32, ADF=0.53, NDF=0.72, RFV=1.50, NUE=9.16.

Table 2.10 – Forage performance indicators (LSMEANS) at 20 DAB in 2017.

Cultivars	Biomass (Mg ha^{-1})	CWU (mm)	CWP (kg ha^{-1} cm^{-1})	LAI (m^{2} m^{-2})	CP (%)	ADF (%)	NDF (%)	RFV	NUE (kg kg^{-1})
Corvallis	5.1 b	261 a	201 b	3.43 b	12.0 a	34.4 a	64.1 a	90 a	74.9 c
Haymore	4.7 b	259 a	185 b	4.64 a	11.4 a	35.7 a	64.0 ab	87 a	71.8 c
Moxie	5.4 b	262 a	206 b	4.60 a	13.0 a	34.7 a	63.6 ab	96 a	71.8 c
Excalibur	6.1 b	287 a	213 b	4.69 a	11.2 a	35.5 a	63.4 ab	90 a	88.8 bc
SS	9.2 a	328 a	387 a	4.10 ab	10.2 a	34.9 a	59.9 b	96 a	181 a
PM	7.0 b	326 a	241 b	4.66 a	14.2 a	34.5 a	61.9 ab	91 a	129 b
Standard Error	1.08	24.8§	28.4§	0.29‡	1.18§	0.79§	0.85§	2.07§	8.49§

*LSMEANS with the same letter are not significantly different according to Bonferroni grouping (α=0.05).

§Standard error for pearl millet: CWU=28.7, CWP=32.8, CP=1.36, ADF=0.92, NDF=0.98, RFV=2.40, NUE=9.80.

‡Standard error for haymore and sorghum sudangrass is 0.25.

Table 2.11 – Proc GLIMMIX output in SAS for seasonal above-ground biomass in 2016 and 2017.

Type 3 Tests of Fixed Effects in 2016				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	66.33	20.97	<.0001
DAP	4	80.07	102.50	<.0001
Entry*DAP	20	80.07	2.67	0.0010
Type 3 Tests of Fixed Effects in 2017				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	17	26.07	<.0001
DAB	4	68	68.31	<.0001
Entry*DAB	20	68	2.66	0.0014

Table 2.12 - Proc GLIMMIX output in SAS for cumulative crop water use in 2016 and 2017.

<table>
<tr><th colspan="5">Type 3 Tests of Fixed Effects in 2016</th></tr>
<tr><th>Effect</th><th>Num DF</th><th>Den DF</th><th>F Value</th><th>Pr > F</th></tr>
<tr><td>Entry</td><td>5</td><td>18</td><td>1.23</td><td>0.3353</td></tr>
<tr><td>DAP</td><td>4</td><td>72</td><td>1332.42</td><td><.0001</td></tr>
<tr><td>Entry*DAP</td><td>20</td><td>72</td><td>1.20</td><td>0.2276</td></tr>
<tr><th colspan="5">Type 3 Tests of Fixed Effects in 2017</th></tr>
<tr><th>Effect</th><th>Num DF</th><th>Den DF</th><th>F Value</th><th>Pr > F</th></tr>
<tr><td>Entry</td><td>5</td><td>17</td><td>3.22</td><td>0.0318</td></tr>
<tr><td>DAB</td><td>4</td><td>68</td><td>233.88</td><td><.0001</td></tr>
<tr><td>Entry*DAB</td><td>20</td><td>68</td><td>0.49</td><td>0.9612</td></tr>
</table>

Table 2.13 – Proc GLIMMIX output for crop water productivity in 2016 and 2017.

Type 3 Tests of Fixed Effects in 2016				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	18	7.89	0.0004
DAP	4	72	14.19	<.0001
Entry*DAP	20	72	2.95	0.0004
Type 3 Tests of Fixed Effects in 2017				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	17	7.52	0.0007
DAB	4	68	1.74	0.1524
Entry*DAB	20	68	2.08	0.0137

Table 2.14 – Proc GLIMMIX output in SAS for leaf area index in 2016 and 2017.

Type 3 Tests of Fixed Effects in 2016				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	18	55.91	<.0001
DAP	3	54	49.77	<.0001
Entry*DAP	15	54	2.84	0.0025
Type 3 Tests of Fixed Effects in 2017				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	17	3.28	0.0296
DAB	4	68	28.60	<.0001
Entry*DAB	20	68	1.77	0.0424

Table 2.15 – Proc GLIMMIX output in SAS for crude protein in 2016 and 2017.

Type 3 Tests of Fixed Effects in 2016				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	12	88.77	<.0001
DAP	4	48	111.90	<.0001
Entry*DAP	20	48	1.93	0.0320
Type 3 Tests of Fixed Effects in 2017				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	17	0.90	0.5021
DAB	4	68	46.32	<.0001
Entry*DAB	20	68	1.82	0.0359

Table 2.16 – Proc GLIMMIX output in SAS for acid detergent fiber in 2016 and 2017.

<table>
<tr><td colspan="5">Type 3 Tests of Fixed Effects in 2016</td></tr>
<tr><td>Effect</td><td>Num DF</td><td>Den DF</td><td>F Value</td><td>Pr > F</td></tr>
<tr><td>Entry</td><td>5</td><td>17.7</td><td>2.94</td><td>0.0418</td></tr>
<tr><td>DAP</td><td>4</td><td>68.11</td><td>8.98</td><td><.0001</td></tr>
<tr><td>Entry*DAP</td><td>20</td><td>68.05</td><td>1.26</td><td>0.2355</td></tr>
<tr><td colspan="5">Type 3 Tests of Fixed Effects in 2017</td></tr>
<tr><td>Effect</td><td>Num DF</td><td>Den DF</td><td>F Value</td><td>Pr > F</td></tr>
<tr><td>Entry</td><td>5</td><td>17</td><td>6.64</td><td>0.0013</td></tr>
<tr><td>DAB</td><td>4</td><td>68</td><td>47.20</td><td><.0001</td></tr>
<tr><td>Entry*DAB</td><td>20</td><td>68</td><td>1.84</td><td>0.0326</td></tr>
</table>

Table 2.17 – Proc GLIMMIX output in SAS for neutral detergent fiber in 2016 and 2017.

Type 3 Tests of Fixed Effects in 2016

Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	12	12.28	0.0002
DAP	4	48	28.63	<.0001
Entry*DAP	20	48	1.21	0.2852

Type 3 Tests of Fixed Effects in 2017

Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	17	3.28	0.0296
DAB	4	68	28.60	<.0001
Entry*DAB	20	68	1.77	0.0424

Table 2.18 – Proc GLIMMIX output in SAS for relative feed value in 2016 and 2017.

Type 3 Tests of Fixed Effects in 2016				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	12	13.43	0.0001
DAP	4	48	21.00	<.0001
Entry*DAP	20	48	1.14	0.3460
Type 3 Tests of Fixed Effects in 2017				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	17	5.99	0.0023
DAB	4	68	57.63	<.0001
Entry*DAB	20	68	3.22	0.0002

Table 2.19 – Proc GLIMMIX output in SAS for nitrogen use efficiency in 2016 and 2017.

Type 3 Tests of Fixed Effects in 2016				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	18	20.53	<.0001
DAP	4	72	63.63	<.0001
Entry*DAP	20	72	2.82	0.0007
Type 3 Tests of Fixed Effects in 2017				
Effect	Num DF	Den DF	F Value	Pr > F
Entry	5	17	45.96	<.0001
DAB	4	68	59.90	<.0001
Entry*DAB	20	68	2.92	0.0005

Table 2.20 – Forage performance indicators (LSMEANS) at 63 DAP in 2017.

Cultivars	Biomass (Mg ha^{-1})	CWU (mm)	CWP (kg ha^{-1} cm^{-1})	LAI (m^{2} m^{-2})	CP (%)	ADF (%)	NDF (%)	RFV	NUE (kg kg^{-1})
Corvallis	5.1 b	261 a	201 ab	3.43 a	12.0 a	34.4 ab	64.1 ab	90 b	74.9 b
Haymore	4.9 b	260 a	190 b	4.62 a	11.1 a	35.5 a	64.9 a	87 b	71.8 b
Moxie	4.9 b	288 a	178 b	4.61 a	14.4 a	32.9 ab	61.7 abc	96 ab	71.6 b
Excalibur	6.1 ab	287 a	213 ab	4.69 a	11.2 a	35.5 a	63.4 ab	90 b	88.8 ab
SS	7.8 a	211 a	376 a	N/A	12.6 a	34.9 ab	59.9 bc	98 ab	113 a
PM	4.7 b	199 a	265 ab	N/A	15.2 a	34.5 b	57.6 c	105 a	68.0 b

Appendix A - 2016 Raw Data

Corvallis: Plots 106, 206, 302, 401. Entry = 1
Haymore: Plots 104, 203, 305, 406. Entry = 2
Moxie: Plots 103, 201, 304, 405. Entry = 3
Excalibur: Plots 105, 202, 301, 404. Entry = 4
Sorghum Sudangrass: Plots 102, 205, 306, 402. Entry =5
Pearl Millet: Plots 101, 204, 303, 403. Entry = 6

Plot	rep	entry	DAP	AGB	AGB	CWU	CWU	CWP	LAI	CP	ADF	NDF
				Mg/ha	kg/ha	mm	cm	kg/ha/cm	m^2/m^2	%	%	%
106	1	1	40	1.96	1963.4	105.3	10.5	186.5	4.05	21.9	29.65	52.54
206	2	1	40	2.76	2755.6	82.0	8.2	336.0	4.49	20.3	30.71	57.10
302	3	1	40	1.64	1642.0	91.8	9.2	179.0	4.07	21.6	29.45	53.21
401	4	1	40	2.10	2104.5	96.8	9.7	217.5	3.99		32.47	
106	1	1	44	3.53	3530.6	122.0	12.2	289.5	4.63	17.6	31.86	57.59
206	2	1	44	3.88	3875.0	96.8	9.7	400.4	4.38	17.8	27.93	58.07
302	3	1	44	3.70	3702.8	111.6	11.2	331.8	4.48	17.9	32.78	58.83
401	4	1	44	3.10	3100.0	102.8	10.3	301.4	3.91		33.23	
106	1	1	48	3.96	3961.1	152.8	15.3	259.2	4.89	17.6	31.65	60.84
206	2	1	48	4.13	4133.3	134.3	13.4	307.7	4.88	16.0	31.62	60.86
302	3	1	48	3.62	3616.7	138.8	13.9	260.6	4.89	16.9	32.18	58.13
401	4	1	48	3.53	3530.6	142.1	14.2	248.4	4.87		35.65	
106	1	1	54	4.22	4219.5	183.9	18.4	229.4	5.21	16.6	31.17	59.27
206	2	1	54	4.65	4650.0	165.8	16.6	280.4	4.81	17.1	30.02	58.66
302	3	1	54	4.22	4219.5	169.6	17.0	248.8	5.14	16.4	30.28	58.33
401	4	1	54	4.05	4047.2	178.5	17.9	226.7	4.81		30.92	
106	1	1	58	4.39	4391.7	209.1	20.9	210.1		15.6	29.92	57.12
206	2	1	58	4.74	4736.1	188.9	18.9	250.7		15.3	31.96	59.82
302	3	1	58	4.31	4305.6	194.4	19.4	221.5		16.4	30.39	58.52
401	4	1	58	5.43	5425.0	208.1	20.8	260.7			32.05	
104	1	2	40	2.07	2066.7	84.0	8.4	245.9	4.12	18.0	32.46	58.74
203	2	2	40	2.53	2527.3	95.2	9.5	265.4	4.28	19.4	31.19	56.91
305	3	2	40	2.07	2067.3	89.0	8.9	232.3	4.54	18.3	31.89	56.74
406	4	2	40	2.67	2669.4	89.8	9.0	297.2	4.00		32.53	
104	1	2	44	3.53	3530.6	95.1	9.5	371.3	4.65	15.9	32.05	58.22
203	2	2	44	4.39	4391.7	111.9	11.2	392.5	4.32	16.4	35.20	59.92
305	3	2	44	3.27	3272.2	104.8	10.5	312.2	4.26	16.0	32.73	57.12
406	4	2	44	3.62	3616.7	111.0	11.1	325.8	5.49		34.08	
104	1	2	48	4.48	4477.8	121.6	12.2	368.2	4.38	15.2	34.55	60.46
203	2	2	48	3.88	3875.0	150.9	15.1	256.8	4.71	14.9	34.27	61.06
305	3	2	48	4.91	4908.3	139.1	13.9	352.9	4.62	15.8	34.23	60.34
406	4	2	48	4.39	4391.7	143.9	14.4	305.1	5.04		30.79	

104	1	2	54	4.13	4133.3	156.5	15.7	264.1	4.42	14.8	30.41	60.39
203	2	2	54	4.91	4908.3	190.1	19.0	258.2	4.96	13.9	35.67	61.44
305	3	2	54	4.05	4047.2	172.2	17.2	235.1	4.81	15.4	32.42	60.08
406	4	2	54	4.74	4736.1	176.1	17.6	269.0	5.29		32.11	
104	1	2	58	3.96	3961.1	187.2	18.7	211.6		14.1	31.16	59.51
203	2	2	58	4.82	4822.2	213.8	21.4	225.6		14.1	32.72	59.00
305	3	2	58	4.13	4133.3	201.4	20.1	205.2		14.6	31.55	60.75
406	4	2	58	3.44	3444.5	204.9	20.5	168.1				
103	1	3	40	3.25	3254.8	103.6	10.4	314.1	4.76	19.3	30.03	53.84
201	2	3	40	3.80	3802.9	119.6	12.0	317.9	4.40	19.3	31.60	54.94
304	3	3	40	2.67	2669.4	100.0	10.0	266.8	5.20	19.9	29.87	56.90
405	4	3	40	1.73	1731.9	96.4	9.6	179.7	4.49		29.71	
103	1	3	44	3.96	3961.1	127.8	12.8	310.1	5.44	17.5	32.09	57.90
201	2	3	44	3.44	3444.5	133.8	13.4	257.4	5.46	17.3	30.79	54.66
304	3	3	44	3.88	3875.0	111.8	11.2	346.6	5.47	16.3	35.37	60.60
405	4	3	44	2.93	2927.8	110.6	11.1	264.8	4.29		30.90	
103	1	3	48	4.99	4994.5	171.1	17.1	291.8	5.64	15.6	33.70	58.17
201	2	3	48	4.99	4994.5	167.0	16.7	299.1	5.47	16.8	35.05	59.40
304	3	3	48	3.96	3961.1	138.0	13.8	286.9	5.08	16.4	33.73	60.12
405	4	3	48	4.05	4047.2	149.0	14.9	271.5	5.03		29.85	
103	1	3	54	4.91	4908.3	202.5	20.3	242.3	5.35	16.5	30.66	59.71
201	2	3	54	5.51	5511.1	195.0	19.5	282.7	5.45	16.7	31.01	59.16
304	3	3	54	5.17	5166.7	174.6	17.5	296.0	5.64	15.8	30.45	58.79
405	4	3	54	4.74	4736.1	185.2	18.5	255.7	5.01		29.99	
103	1	3	58	5.34	5338.9	228.2	22.8	234.0		15.6	30.79	58.38
201	2	3	58	5.34	5338.9	218.8	21.9	244.0		16.0	30.70	55.60
304	3	3	58	4.91	4908.3	200.7	20.1	244.6		15.8	32.29	58.61
405	4	3	58	4.39	4391.7	205.2	20.5	214.0				
105	1	4	40	3.69	3691.9	106.5	10.7	346.5	4.83	18.2	31.39	57.99
202	2	4	40	4.55	4547.5	104.4	10.4	435.7	4.81	18.3	35.91	56.50
301	3	4	40	4.26	4258.9	81.2	8.1	524.2	4.48	17.4	32.18	58.74
404	4	4	40	2.93	2927.8	79.7	8.0	367.4	3.76		31.86	
105	1	4	44	4.48	4477.8	121.1	12.1	369.8	4.93	16.3	33.06	58.19
202	2	4	44	4.05	4047.2	118.0	11.8	343.0	5.59	15.6	33.59	57.88
301	3	4	44	4.39	4391.7	95.5	9.6	459.7	5.17	15.2	34.54	59.95
404	4	4	44	3.79	3788.9	104.2	10.4	363.6	4.10		32.99	
105	1	4	48	5.34	5338.9	161.7	16.2	330.2	5.22	15.3	33.44	59.67
202	2	4	48	5.25	5252.8	152.4	15.2	344.6	5.53	16.7	33.08	60.63
301	3	4	48	5.34	5338.9	129.5	13.0	412.2	5.03	15.9	32.37	60.34
404	4	4	48	4.31	4305.6	142.8	14.3	301.6	4.51		33.93	
105	1	4	54	5.08	5080.6	203.8	20.4	249.3	5.45	14.2	31.76	59.78
202	2	4	54	5.25	5252.8	182.5	18.2	287.8	5.26	12.8	33.89	59.70
301	3	4	54	6.03	6027.8	161.9	16.2	372.3	5.3	14.4	34.08	60.91

404	4	4	54	6.20	6200.0	176.5	17.6	351.3	4.65		33.07	
105	1	4	58	5.60	5597.2	221.9	22.2	252.2		13.6	32.16	57.88
202	2	4	58	4.82	4822.2	198.6	19.9	242.8		14.2	30.50	58.81
301	3	4	58	4.91	4908.3	183.2	18.3	268.0		14.8	32.09	59.89
404	4	4	58	4.22	4219.5	202.5	20.3	208.3				
102	1	5	40	3.10	3100.0	96.5	9.7	321.2	2.62	19.7	30.53	55.33
205	2	5	40	3.27	3272.2	107.94	10.79	303.15	2.43	18.9	29.24	51.49
306	3	5	40	3.53	3530.6	97.88	9.79	360.70	3.19	19.1	29.90	51.26
402	4	5	40	2.41	2411.1	82.37	8.24	292.73	1.92		29.50	
102	1	5	44	4.91	4908.3	111.99	11.20	438.27	2.88	16.0	32.26	54.23
205	2	5	44	2.93	2927.8	114.68	11.47	255.31	2.47	16.4	37.51	54.07
306	3	5	44	3.88	3875.0	108.18	10.82	358.19	3.03	16.9	32.11	54.90
402	4	5	44	3.44	3444.5	90.17	9.02	382.00	2.45		29.79	
102	1	5	48	7.49	7491.7	155.27	15.53	482.51	3.6	14.8	33.78	57.68
205	2	5	48	4.56	4563.9	140.79	14.08	324.17	3.31	16.1	31.37	55.60
306	3	5	48	6.29	6286.1	134.02	13.40	469.04	3.91	15.8	32.00	55.41
402	4	5	48	4.82	4822.2	128.75	12.87	374.55	3.76		34.12	
102	1	5	54	7.15	7147.2	194.52	19.45	367.42	3.914	12.4	30.71	60.24
205	2	5	54	4.56	4563.9	162.70	16.27	280.51	3.67	15.2	30.63	58.27
306	3	5	54	6.98	6975.0	158.07	15.81	441.26	3.5	13.7	33.20	57.69
402	4	5	54	6.29	6286.1	163.40	16.34	384.70	3.36		32.01	
102	1	5	58	6.11	6113.9	215.14	21.51	284.19		14.3	31.48	55.32
205	2	5	58	7.41	7405.6	184.96	18.50	400.38		12.3	30.89	55.91
306	3	5	58	7.23	7233.3	180.48	18.05	400.78		10.4	33.80	58.72
402	4	5	58	9.99	9988.9	183.84	18.38	543.36				
101	1	6	40	3.19	3186.1	111.48	11.15	285.81	5.32	21.9	26.48	53.11
204	2	6	40	4.65	4650.0	113.27	11.33	410.51	6.30	21.3	29.38	54.65
303	3	6	40	4.05	4047.2	118.58	11.86	341.32	5.48	22.3	29.86	53.41
403	4	6	40	2.84	2841.7	67.52	6.75	420.84	4.92		27.22	
101	1	6	44	4.74	4736.1	139.12	13.91	340.43	6.30	17.9	33.28	56.60
204	2	6	44	5.68	5683.3	132.72	13.27	428.22	6.84	19.7	31.64	54.13
303	3	6	44	5.51	5511.1	128.30	12.83	429.55	5.76	19.3	31.36	54.12
403	4	6	44	4.82	4822.2	84.04	8.40	573.78	5.73		33.43	
101	1	6	48	6.46	6458.3	179.98	18.00	358.83	7.05	18.2	32.51	56.83
204	2	6	48	7.66	7663.9	167.24	16.72	458.25	7.27	18.9	32.12	57.21
303	3	6	48	6.89	6888.9	164.96	16.50	417.62	7.18	20.0	33.39	55.86
403	4	6	48	6.03	6027.8	119.45	11.95	504.62	7.08		30.82	
101	1	6	54	7.32	7319.5	220.22	22.02	332.37	6.57	17.3	30.78	57.70
204	2	6	54	8.09	8094.5	213.51	21.35	379.11	7.31	17.6	31.80	56.06
303	3	6	54	7.92	7922.2	189.34	18.93	418.41	7.68	17.3	34.37	58.82
403	4	6	54	5.34	5338.9	153.31	15.33	348.23	7.62		33.62	
101	1	6	58	6.20	6200.0	248.27	24.83	249.73		17.7	31.58	56.06
204	2	6	58	6.63	6630.6	236.69	23.67	280.14		17.6	33.01	58.72

303	3	6	58	7.23	7233.3	221.69	22.17	326.28		17.6	33.34	59.30
403	4	6	58	8.70	8697.2	185.54	18.55	468.75				

Appendix B - 2017 Raw Data

Corvallis: Plots 106, 206, 302, 401. Entry = 1
Haymore: Plots 104, 203, 305, 406. Entry = 2
Moxie: Plots 103, 201, 304, 405. Entry = 3
Excalibur: Plots 105, 202, 301, 404. Entry = 4
Sorghum Sudangrass: Plots 102, 205, 306, 402. Entry =5
Pearl Millet: Plots 101, 204, 303, 403. Entry = 6

Plot	rep	entry	DAB	AGB	AGB	CWU	CWU	CWP	LAI	CP	ADF	NDF
				Mg/ha	kg/ha	mm	cm	kg/ha/cm	m^2/m^2	%	%	%
106	1	1	0	1.40	1404.3	83.0	8.3	169.2	2.21	16.13	29.42	59.83
206	2	1	0	1.29	1291.7	145.9	14.6	88.5	2.84	15.94	28.59	59.08
302	3	1	0	2.58	2583.3	133.7	13.4	193.2	2.87	17.13	28.48	58.64
401	4	1	0	2.32	2318.8	172.1	17.2	134.7	2.71	19.06	28.97	58.02
106	1	1	5	1.64	1636.1	109.4	10.9	149.5	3.11	13.94	32.56	62.46
206	2	1	5	3.19	3186.1	178.5	17.8	178.5	4	13.75	33.92	61.69
302	3	1	5	1.38	1377.8	165.2	16.5	83.4	3.13	17.88	31.47	59.77
401	4	1	5	2.41	2411.1	195.9	19.6	123.1	2.76	15.19	31.92	58.79
106	1	1	10	2.76	2755.6	116.6	11.7	236.4	4.07	12.31	32.72	62.76
206	2	1	10	4.82	4822.2	222.7	22.3	216.6	4.2	10.94	34.31	61.95
302	3	1	10	3.62	3616.7	221.5	22.1	163.3	3.53	12.88	32.49	61.80
401	4	1	10	2.67	2669.4	230.7	23.1	115.7	4.6	16.13	31.40	60.20
106	1	1	15	3.70	3702.8	164.9	16.5	224.5	3.81	10.25	33.13	61.44
206	2	1	15	3.96	3961.1	250.2	25.0	158.3	4.73	9.38	33.61	62.64
302	3	1	15	4.56	4563.9	249.6	25.0	182.9	4.3	10.69	34.89	62.13
401	4	1	15	3.70	3702.8	282.4	28.2	131.1	4.36	12.31	32.78	62.64
106	1	1	20	4.39	4391.7	180.3	18.0	243.6	3.82	9.63	36.03	65.26
206	2	1	20	5.60	5597.2	279.4	27.9	200.3		10.81	33.22	62.98
302	3	1	20	5.17	5166.7	273.1	27.3	189.2	2.88	14.13	34.19	64.03
401	4	1	20	5.34	5338.9	311.1	31.1	171.6	3.58	13.38	33.99	64.10
104	1	2	0	2.09	2091.8	109.1	10.9	191.7	2.73	15.69	30.87	62.14
203	2	2	0	1.51	1510.6	118.8	11.9	127.2	2.71	16.19	29.76	61.24
305	3	2	0	1.82	1823.0	123.4	12.3	147.7	2.33	16.19	30.06	59.10
406	4	2	0	2.74	2741.1	143.4	14.3	191.2	2.24	14.56	32.03	61.76
104	1	2	5	3.88	3875.0	138.7	13.9	279.3	4.37	15.19	34.71	63.24
203	2	2	5	2.58	2583.3	148.4	14.8	174.0	4.14	15.00	32.80	61.11
305	3	2	5	2.24	2238.9	153.0	15.3	146.3	4.24	16.50	32.30	60.13
406	4	2	5	3.19	3186.1	173.0	17.3	184.1	3.39	13.00	34.08	62.14
104	1	2	10	3.27	3272.2	161.2	16.1	203.0	5.06	10.94	37.67	65.45
203	2	2	10	2.93	2927.8	191.1	19.1	153.2	5.14	12.13	34.24	63.93
305	3	2	10	3.27	3272.2	185.6	18.6	176.3	4.05	12.31	36.31	66.35
406	4	2	10	3.01	3013.9	205.4	20.5	146.8	4.72	9.75	36.65	64.54

104	1	2	15	6.72	6716.7	201.4	20.1	333.5	4.53	9.88	36.25	65.40
203	2	2	15	5.51	5511.1	254.4	25.4	216.6	4.64	9.00	37.30	65.27
305	3	2	15	5.86	5855.6	236.3	23.6	247.8	4.59	9.88	36.28	65.99
406	4	2	15	4.13	4133.3	246.9	24.7	167.4	4.57	9.06	34.71	63.62
104	1	2	20	5.34	5338.9	229.0	22.9	233.2	4.34	13.94	38.00	65.93
203	2	2	20	4.74	4736.1	281.4	28.1	168.3	3.96	11.25	34.30	62.58
305	3	2	20	5.51	5511.1	265.2	26.5	207.8	4.57	10.25	37.46	67.41
406	4	2	20	4.05	4047.2	265.9	26.6	152.2	5.61	8.94	34.81	63.59
103	1	3	0	2.26	2258.9	101.8	10.2	221.8	3.08	17.69	28.35	58.19
201	2	3	0	1.78	1780.3	125.0	12.5	142.4	3.14	16.88	29.40	59.64
304	3	3	0	1.64	1636.1	143.9	14.4	113.7		15.94	30.81	57.94
405	4	3	0	2.57	2571.1	160.7	16.1	160.0	3.52	14.69	31.00	57.33
103	1	3	5	2.50	2497.2	122.7	12.3	203.5	4.39	15.06	33.43	61.11
201	2	3	5	2.67	2669.4	170.4	17.0	156.6	4.59	15.56	32.70	60.32
304	3	3	5	3.19	3186.1	237.1	23.7	134.4	4.08	14.06	33.42	62.72
405	4	3	5	2.41	2411.1	190.4	19.0	126.7	3.66	13.31	33.83	61.79
103	1	3	10	4.13	4133.3	154.7	15.5	267.1	6.1	15.25	32.70	60.34
201	2	3	10	3.88	3875.0	199.7	20.0	194.0	5.03	11.44	33.38	62.25
304	3	3	10	4.82	4822.2	296.7	29.7	162.5	3.2	12.94	32.37	61.87
405	4	3	10	3.44	3444.5	222.4	22.2	154.9	4.85	10.69	34.32	61.84
103	1	3	15	4.13	4133.3	190.2	19.0	217.4	4.99	14.44	32.75	59.55
201	2	3	15	5.08	5080.6	257.0	25.7	197.7	4.5	10.44	34.30	62.16
304	3	3	15	3.70	3702.8	329.3	32.9	112.5	4.52	12.94	34.15	61.72
405	4	3	15	4.13	4133.3	271.8	27.2	152.1	4.91	8.81	34.17	60.79
103	1	3	20	4.48	4477.8	213.4	21.3	209.8	4.26	15.13	33.97	63.03
201	2	3	20	5.68	5683.3	277.0	27.7	205.2	4.56	14.06	32.21	60.04
304	3	3	20	3.62	3616.7	370.9	37.1	97.5		16.31	30.08	59.75
405	4	3	20	5.86	5855.6	292.2	29.2	200.4	5.01	12.13	35.19	64.11
105	1	4	0	1.82	1822.1	118.2	11.8	154.2	2.45	15.00	30.91	58.58
202	2	4	0	1.70	1700.4	151.4	15.1	112.3	2.7	16.25	28.99	59.36
301	3	4	0	2.33	2325.0	140.2	14.0	165.8	2.95	15.00	31.08	60.87
404	4	4	0	2.85	2847.9	146.4	14.6	194.5	3.21	17.06	29.87	59.08
105	1	4	5	3.10	3100.0	147.8	14.8	209.8	4.59	11.81	36.69	64.21
202	2	4	5	2.76	2755.6	183.1	18.3	150.5	4.03	14.81	34.19	61.25
301	3	4	5	3.44	3444.5	188.8	18.9	182.5	4.82	15.25	33.17	62.24
404	4	4	5	4.39	4391.7	176.0	17.6	249.5	4.54	15.00	35.00	61.63
105	1	4	10	3.70	3702.8	178.8	17.9	207.1	5.06	9.63	31.96	64.69
202	2	4	10	4.39	4391.7	222.4	22.2	197.4	5.44	10.94	35.03	63.70
301	3	4	10	4.13	4133.3	246.8	24.7	167.5	4.47	10.94	33.24	60.52
404	4	4	10	5.34	5338.9	224.7	22.5	237.6	3.15	11.19	35.12	62.52
105	1	4	15	5.68	5683.3	226.2	22.6	251.3	4.78	10.19	36.90	65.20
202	2	4	15	6.11	6113.9	272.3	27.2	224.5	4.54	8.38	34.79	62.35
301	3	4	15	5.60	5597.2	277.1	27.7	202.0	6.11	8.69	34.55	62.86

404	4	4	15	6.46	6458.3	270.0	27.0	239.2	4.76	8.00	35.25	59.78
105	1	4	20	5.94	5941.7	253.8	25.4	234.1	4.06	12.75	36.33	65.86
202	2	4	20	5.94	5941.7	288.9	28.9	205.7	4.82	11.63	34.05	61.67
301	3	4	20	6.03	6027.8	303.1	30.3	198.8		10.88	35.78	63.69
404	4	4	20	6.37	6372.2	300.7	30.1	211.9	5.19	9.56	35.64	62.56
102	1	5	0	6.98	6975.0	169.3	16.9	411.9		15.00	32.92	58.26
205	2	5	0	6.80	6802.8	255.1	25.5	266.7		10.81	34.46	60.82
306	3	5	0	8.96	8955.6	226.2	22.6	396.0		12.19	35.83	61.90
402	4	5	0	8.35	8352.8	194.6	19.5	429.2		12.38	32.33	57.20
102	1	5	5	10.16	10161.1	204.4	20.4	497.1	3.83	13.69	33.55	59.32
205	2	5	5	9.90	9902.8	297.6	29.8	332.8	3.92	11.81	35.96	62.62
306	3	5	5	13.95	13950.0	259.8	26.0	536.9	3.44	11.56	36.96	62.47
402	4	5	5	8.35	8352.8	210.4	21.0	397.0	3.56	13.31	35.43	61.98
102	1	5	10	11.45	11452.8	200.0	20.0	572.7	3.59	12.81	37.97	61.77
205	2	5	10	8.18	8180.6	300.7	30.1	272.0	3.55	12.19	36.07	62.17
306	3	5	10	13.09	13088.9	340.2	34.0	384.7	3.96	9.94	38.35	62.89
402	4	5	10	10.51	10505.6	226.9	22.7	462.9	4.47	10.19	35.95	61.36
102	1	5	15	9.39	9386.1	244.1	24.4	384.5	4.01	13.94	35.52	60.87
205	2	5	15	6.63	6630.6	324.3	32.4	204.5	4.57	11.50	34.98	61.88
306	3	5	15	9.73	9730.6	397.0	39.7	245.1	4.16	9.56	37.16	63.35
402	4	5	15	11.63	11625.0	255.0	25.5	455.9	4.46	8.69	35.65	61.34
102	1	5	20	13.95	13950.0	268.3	26.8	520.0	4.25	12.00	33.61	58.06
205	2	5	20	10.42	10419.5	348.1	34.8	299.3	4.53	11.75	34.90	60.20
306	3	5	20	14.38	14380.6	413.8	41.4	347.5	3.72	7.38	36.97	61.14
402	4	5	20	10.76	10763.9	281.2	28.1	382.8	3.89	10.19	33.93	60.19
101	1	6	0	6.20	6200.0	136.3	13.6	454.8		20.94	32.35	59.91
204	2	6	0	3.27	3272.2	245.6	24.6	133.2		11.44	30.42	56.73
303	3	6	0									
403	4	6	0	4.48	4477.8	214.8	21.5	208.4		13.25	29.63	56.09
101	1	6	5	5.51	5511.1	170.0	17.0	324.2	5.92	20.88	31.07	58.66
204	2	6	5	4.22	4219.5	279.3	27.9	151.1	4.76	10.81	30.97	58.59
303	3	6	5									
403	4	6	5	4.39	4391.7	256.1	25.6	171.5	4.58	12.19	31.59	58.21
101	1	6	10	5.86	5855.6	202.5	20.3	289.2	4.95	22.25	32.70	60.47
204	2	6	10	3.44	3444.5	292.2	29.2	117.9	3.95	10.75	35.30	60.51
303	3	6	10									
403	4	6	10	5.77	5769.5	263.8	26.4	218.7	4.02	8.06	33.67	60.07
101	1	6	15	7.15	7147.2	239.1	23.9	298.9	4.33	18.38	35.84	62.90
204	2	6	15	6.46	6458.3	326.6	32.7	197.7	4.42	11.06	34.58	62.44
303	3	6	15									
403	4	6	15	5.25	5252.8	288.0	28.8	182.4	4.83	9.44	35.60	62.96
101	1	6	20	9.99	9988.9	267.6	26.8	373.3	4.44	17.25	36.81	64.02
204	2	6	20	9.30	9300.0	347.8	34.8	267.4	4.98	8.63	36.67	61.71

303	3	6	20									
403	4	6	20	7.15	7147.2	316.34	31.63	225.9	4.56	14.75	34.43	61.94

Appendix C - SAS Code

```
proc glimmix data = NWREC_TEFF_2017;
class entry rep DAP (OR DAB);
Model variable = entry | DAP (OR DAB) / s ddfm = KR;
random rep(entry) / subject = rep(entry) Type = CS;
lsmeans entry | DAP (OR DAB) / lines cl pdiff adjust = Bon;
By DAP (or DAB)
run;

data NWREC_TEFF_2017;
set NWREC_TEFF_2017;
logagb = log(agb);
keep plot rep entry DAB agb logagb cwu cwp lai cp ndf adf;
run;
```