Improving Management and Species Selection of Warm-Season Forage Grasses for Southeast Production Systems

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DEDICATION

To my husband:

Keegan Anthony Gelley

To our daughter:

Bethany Elaine Gelley

To my parents:

Joyce Louise Ritchie

Kenneth Leroy Ritchie Jr.

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ABSTRACT

Beef producers need drought tolerant options when selecting forage grasses and also practical methods to estimate forage nutritive value, which this study aims to provide for warm-season grasses. The objective of the first experiment was to develop estimates of warm-season forage nutritive value and herbage mass based on harvest timing. The experiment was conducted from 2013 to 2015 at the University of Tennessee Plateau AgResearch and Education Center (PREC) in Crossville, TN. Four species were evaluated, each for two years: bermudagrass [*Cynodon dactylon* (L.) Pers. cv. Vaughn's # 1], switchgrass [*Panicum virgatum* (L.) cv. Alamo], sorghum-sudangrass [*Sorghum bicolor* (L.) Moench ×*Sorghum Sudanese* (P.) Stapf, cv. FSG208BMR], and crabgrass [*Digitaria sanguinalis*(L.) cv. Quick-N-Big]. Results indicate that there is a strong linear relationship between herbage mass and crude protein in both switchgrass and sorghum-sudangrass which could be used to estimate forage nutritive value based on herbage mass. The objective of the second experiment was to use water use efficiency (WUE) to evaluate the productive potential of grass species during limited rainfall. This experiment consisted of a greenhouse study followed by a field study. Water use efficiency data was collected through a greenhouse experiment held at The University of Tennessee, Knoxville. Species tested included crabgrass (*Digitaria sanguinalis* cv. 'Red River'), switchgrass (*Panicum virgatum* (L.) cv. Alamo), big bluestem (*Andropogon gerardii* cv. 'OZ-70'), indiangrass (*Sorghastum nutans* cv. 'Rumsey'), eastern gamagrass (*Tripsacum dactyloides* cv. 'Pete'), and bermudagrass (*Cynodon dactylon* cv. 'Vaughn's #1'). Results aided in forming hypotheses of species performance in the field. The field experiment took place at the Highland Rim

AgResearch and Education Center (HRREC) in Springfield, Tennessee and the Ames Plantation (APREC) AgResearch and Education Center in Grand Junction, Tennessee during the growing seasons of 2014 and 2015. Results from the second experiment indicated that WUE of switchgrass and eastern gamagrass were greater than indiangrass and bigbluestem at APREC , but species did not differ at HRREC. In addition WUE differed with time of year at HRREC, but did not at APREC. Temperature and WUE were positively correlated at both locations suggesting that as temperature increases, WUE increases.

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Chapter 1:

ABBREVIATIONS AND SYMBOLS

ADF	acid detergent fiber, g ADF kg^{-1} DM
APREC	Ames Plantation AgResearch and Education Center- Grand Junction, TN
C_3	cool-season grasses
C_4	warm-season grasses
CP	crude protein, g CP kg^{-1} DM
DM	dry matter
DPW	days post watering
ETREC	East Tennessee AgResearch and Education Center- Knoxville, TN
HAR	herbage accumulation rate
HM	herbage mass, kg DM ha^{-1}
HRREC	Highland Rim AgResearch and Education Center- Springfield, TN
IVTDMD	*in-vitro* dry matter digestibility
NDF	neutral detergent fiber, g ADF kg^{-1} DM
NIRS	near-infrared spectroscopy
NDFD	neutral detergent fiber digestibility, g NDFD kg^{-1} NDF
NRCS	Natural Resource Conservation Service
PREC	Plateau AgResearch and Education Center- Crossville, TN
USDA	United States Department of Agriculture
UT	University of Tennessee
UTIA	University of Tennessee Institute of Agriculture
WUE	water-use efficiency
iWUE	instantaneous water-use efficiency, µmol CO_2 mol H_2O^{-1}

INTRODUCTION

Utilizing Warm-Season Grasses in Southeastern Forage Systems

Warm-season grasses (C_4) can be used to increase pasture yield, extend the grazing season, and utilize soils of poor fertility and/or low water availability in the Southern United States. However, cool-season grass (C_3) species are often recommended for use in ruminant production systems because they provide high quality forage. In general, C_3 grasses have high nutritive value and high digestibility (Bailey, 1973; Ball et al., 2008; Nave et al., 2013). However in the Southeast, cool-season grass productivity is reduced during the hot summer months and forage availability declines. In order to extend grazing season and reduce hay needs, the use of warm-season grasses can be considered a good alternative.

The C_3 photosynthetic pathway of cool-season grasses enables photorespiration under high temperatures (Taiz and Zeiger, 2002). During photorespiration the stomata of these plant species close reducing the uptake of carbon dioxide (CO_2) and increasing the concentration of oxygen (O_2). At this point the enzyme Rubisco will act as an oxygenase instead of a carboxylase and previously fixed CO_2 will be released from the plant (Taiz and Zeiger, 2002). This process consumes more energy than it produces. Warm-season grasses have the potential to complement cool-season grass forage availability due to its C_4 photosynthetic pathway (Griffen and Jung, 1983). The C_4 photosynthetic pathway prevents photorespiration from occurring. Under heat and water stress plants with C_4 photosynthesis are more efficient than those with C_3 photosynthesis. C_4 plants have lower transpiration ratios, higher photosynthetic rates, lower CO_2 compensation points, and higher light saturation points than C_3 plants (Taiz and Zeiger, 2002). Therefore, warm-season grasses can produce greater herbage mass yields under high temperatures and during times of reduced water availability (Nelson and Moser, 1994).

Warm-season grasses are known to often have lower nutritive values than cool-season grasses (Wilson and Minson, 1980). Crude protein (CP) and digestibility may be comparable under cool conditions, but at high temperatures the plants mature more quickly, accumulating more cell wall carbohydrates and less intracellular carbohydrates, which causes CP and digestibility to decrease (Buxton and Fales, 1994). If not managed correctly, a diet of solely warm-season grasses may lead to animals requiring nutrient supplementation (Wilson and Minson, 1980). Even so, utilizing these species provides forage when cool-season species are unavailable. This can result in reduced hay needs, extending the grazing season, and potentially increasing stocking rates, which may lead to greater profitability for producers (Ball et. al, 2008).

Drought conditions often force producers to purchase supplemental feed for cattle, reducing profitability. Climate data collected over the past decade shows that summers in the Southeast are becoming warmer and dryer (U.S. Drought Monitor, 2014). Climatologists expect this trend to continue in the future (Konrad II and Fuhrmann, 2013). Warm-season grasses are adapted to complete their life cycles under such conditions. Along with the C_4 photosynthetic pathway, these species often have deep rooting systems which enable the plants to utilize soil water unavailable to cool-season species (Keyser et al., 2013). Therefore increasing the use of warm-season grass species could increase the sustainability of grazing pastures for future generations.

Maximizing Forage Nutritive Value

Previous studies have confirmed that forage nutritive value declines with maturity and that digestibility decreases following the first forage harvest (Jarl and Helleday, 1951; Vona et al., 1984; George and Obermann, 1989; Moore et al., 1991; Burns et al., 1997; Difante et al., 2008; Nave et al., 2014; Richner et al., 2014; Temu et al., 2014). To compensate for warm temperatures and low water, C_4 grasses mature quickly developing high levels of fiber, especially lignin (Buxton and Fales, 1994). As the plant matures older leaves die, fewer young leaves are produced, and the plant stem to green leaves ratio significantly increases (Wilson and Minson, 1980). Therefore, forage nutritive value will be the highest at the beginning of the growing season and any regrowth that follows a defoliation event will become more fibrous and less digestible than the previous growth. However, the amount of forage accumulated is lowest at the beginning of the season. With appropriate management, warm-season forage can be harvested at a point where forage nutritive value and yield meet the goals of the production system. In some systems high nutritive value will be most important and yield will be sacrificed to meet the goal desired. In other systems yield will be of greater concern and nutritive value will be compromised to achieve the desired yield.

In order to estimate forage nutritive value in the field, practical methods for estimation need to be available. Multiple models based on age, morphology, and weather have been developed for cool-season forages (Fick et. al, 1994). In the 1980s Fick and Onstad developed computer models to predict alfalfa quality using weather and environmental factors, leafiness, and stage of development. In 1989, Thompson et al. predicted cool-season grass digestibility based on air temperature, sunshine duration, and photoperiod change using multiple regression. Additional prediction models were developed for alfalfa based on leafiness (Kalu et. al, 1990). While these computer models were useful, they were still not practical for livestock producers. The equations developed were practical but biased, requiring recalibration for specific environments (Fick et. al, 1994). A simpler method was developed by Hintz and Albrecht (1991) based on height and stage of mature alfalfa stems, which successfully predicted neutral detergent fiber. While these methods were developed for legume crops, few were developed specifically for grasses.

More recently, Nave et al. (2013) fit a linear model to estimate neutral detergent fiber digestibility (NDFD) from herbage mass (HM) in cool-season grasses. Correlations between proportion of lamina, proportion of dead material, age, HM, neutral detergent fiber (NDF), *in vitro* true digestibility (IVTDMD), and NDFD indicated strong relationships between morphological components and nutritive value. Regression equations were developed to describe the relationship between NDFD and HM, which proved to be the most reliable predictor of forage nutritive value. These results can allow producers to estimate forage nutritive value of cool-season grasses from a simple collection of pasture dry matter (DM) to determine the appropriate time to begin grazing or to take a hay cutting (Nave et. al, 2013).

Models similar to those described previously are lacking for warm-season grasses. Crude protein has been successfully predicted in a timely manner using canopy reflectance analysis in bermudagrass (Starks et al., 2006). However, this method requires specialized equipment to create predictions. Developing and improving predictive models for warm-season grasses, similar to those developed for cool-season species, has the potential to improve grazing management in the Southeast.

Utilizing Warm-Season Grasses for Drought Tolerance

In 2007, the Southeast experienced an intense drought forcing many beef producers to downsize or eliminate their herds in an attempt to cope with the lack of forage (USDA NASS, 2015). Increasing the use of warm-season grasses in cattle systems could help minimize the impacts of future droughts and assist in maintaining beef production, which is the United States' largest agricultural sector (USDA NASS, 2015).

As previously discussed, C_4 photosynthesis is more efficient than C_3 photosynthesis when water availability is low (Taiz and Zeiger, 2002). High photosynthesis rates and low transpiration rates result in C_4 plants having higher WUE. Water use efficiency can be described as the amount of water the plant uses to produce one unit of plant material (Kramer, 1980). Moreover, C_4 plants have higher WUE than C_3 plants, which results in an increased tolerance to drought (Taiz and Zeiger, 2002).

For many years different varieties of bermudagrass have been recommended and used for summer production (Murata and Iyama, 1962). However, there are other warm-season species that may be suitable candidates. To obtain an immediate alternative, annual species can be established to provide summer forage (Anderson and Guyer, 1986). Species such as sorghum-sudangrass hybrids and pearl millet produce large amounts of leafy forage in a short timeframe. In addition to fresh forage, these species can be harvested for hay or silage. Crabgrass can also be an option. It is a vigorous grass that reproduces by seeds and spreads by stolons, with a high leaf to stem ratio, high animal intake, and high nutritive value (Bosworth et al., 1980).

Native perennial warm-season grasses, such as switchgrass and big bluestem, may also be suitable candidates to establish for drought tolerance (Anderson and Matches, 1986). These species are fully adapted to the region's climate, have few pest and disease problems, and have deep root systems (Keyser et al. 2013). In addition to large root masses, these species produce high amounts of HM, which when managed for grazing or hay production can provide enough energy to support animal growth and development (Griffen and Jung, 1983; Vona et al., 1984; Temu et al., 2014).

For agronomists, WUE is equal to water used in evapotranspiration divided by dry matter yield. It is often reported as grams of dry matter produced per kilogram of water (Ghannoum et al., 2002). To measure WUE, plants are grown in a controlled environment, with specified watering patterns, and dry matter collected. It is difficult to accurately measure WUE under field conditions, because water inputs and soil moisture are highly variable (Kramer, 1983).

Physiologists use data based on photosynthesis and gas exchange of individual leaves to measure WUE expressed as milligrams of carbon dioxide diffused per gram of water (Kramer, 1983). A portable photosynthesis meter that measures gas exchange can be used to collect instantaneous WUE values (iWUE) (LI-COR, 2011). The LI-6400 XT is an instrument capable of measuring photosynthesis and transpiration rates at specific areas on active leaves (LI-COR Biosciences, Lincoln, Nebraska). Once this data is collected the values are used to calculate WUE by dividing photosynthetic rate by transpiration rate to give the percentage of water used for photosynthesis (LI-COR, 2011).

While these measurements are relatively quick, they are highly dependent on controlled factors. Light intensity and temperature must be consistent during data collection because they have great impacts on both photosynthesis and transpiration (Verma et al., 1988). In order to collect truly representative samples, data must be collected from leaves that are photosynthetically active (LI-COR, 2011).

Impact of Research Topic

Utilizing warm-season grasses in pastures in the Southeast can provide producers with a supply of quality forage in mid-summer. Developing tools to predict nutritive value can assist producers in determining the appropriate times to cut or graze forage for their systems. Identifying species with high WUEs can also help producers plan ahead for future droughts. This study aims to do both, in order to improve pasture management for beef cattle production systems across the Southeastern United States.

CHAPTER 1:

Relationship of Forage Nutritive Value to Herbage Mass of Four Warm-Season Forage Grasses

ABSTRACT

In order to provide animals with high quality forage, practical methods are needed to estimate nutritive value to optimize harvest timing. The objective of this study was to develop real-time estimations of warm-season forage nutritive value leading to better forage management practices. The experiment was conducted at the University of Tennessee Plateau AgResearch and Education Center in Crossville, TN, from 2013 to 2015. Four forages were evaluated, each for two years: switchgrass [*Panicum virgatum* (L.) cv. Alamo], sorghum-sudangrass [*Sorghum bicolor* (L.) Moench ×*Sorghum Sudanese* (P.) Stapf, cv. FSG208BMR], bermudagrass [*Cynodon dactylon* (L.) Pers. cv. Vaughn's # 1] and crabgrass [*Digitaria sanguinalis*(L.) cv. Quick-N-Big]. Monthly cutting initiations and a height prescribed cutting were established for each species. Each management strategy was replicated four times and arranged in a randomized complete block design. Weekly samples were collected to determine morphological composition and nutritive value. Forage nutritive value was analyzed using near-infrared spectroscopy. Morphological composition was consistently correlated to crude protein (CP) for all species except crabgrass, which suggests morphological composition could serve as a visual tool for producers to estimate forage nutritive value. Strong linear relationships existed between herbage mass (HM) and CP in both switchgrass and sorghum-sudangrass. There was a moderately strong relationship between neutral detergent fiber digestibility (NDFD) and HM in switchgrass but not for any other species. These relationships could be used by producers to estimate forage nutritive value based on pasture HM.

INTRODUCTION

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Previous studies have confirmed that forage nutritive value declines with maturity and that digestibility decreases following the first forage harvest (Jarl and Helleday, 1951; Vona et al., 1984; George and Obermann, 1989; Moore et al., 1991; Burns et al., 1997; Difante et al., 2008; Nave et al., 2014; Richner et al., 2014; Temu et al., 2014). To compensate for warm temperatures and low water, C_4 grasses mature quickly developing high levels of fiber, especially lignin (Buxton and Fales, 1994). With appropriate management, warm-season forage can be harvested at a point where forage nutritive value and yield meet the goals of the production system. However, few practical field methods for estimating forage nutritive value have been developed.

Methods for practical estimation of neutral detergent fiber (NDF) and crude protein (CP) for cool-season grasses based on age, morphology, and weather have been studied (Fick, 1994). Nave et al. (2013) found a relationship between herbage accumulation rate (HAR) and neutral detergent fiber digestibility (NDFD) in stands of cool-season grasses. This enabled the fitting of a linear model to estimate NDFD from herbage mass. Real-time estimations of CP content in bermudagrass have been made successfully via canopy reflectance analysis (Starks et al., 2006). However, this method requires specialized equipment to create predictions. Developing and improving predictive models for warm-season grasses, similar to those developed for cool-season species, has the potential to improve grazing management in the Southeast.

The objective of this study was to develop practical estimations of warm-season grasses nutritive value based on the relationship between herbage mass (HM) and nutritive value variables. It was hypothesized that as HM increased, forage nutritive value would decrease and that early cutting initiation dates followed by regular harvestings would lead to lower forage nutritive value throughout the growing-season. If significant relationships between forage nutritive value variables and HM are detected, this information could assist in explaining differences in forage nutritive value across warm-season grasses growing season.

MATERIALS AND METHODS

Site Description

This study was conducted at the Plateau AgResearch and Education Center (PREC) in Crossville, Tennessee (36° 0’ N, 85° 7’ W, 580-m elevation) from June to September 2013 to 2015. Four experiments (one for each species) were conducted with experimental units that were 3 x 4.5 m plots arranged in a randomized complete block design with four replications. Soil conditions on location were Lonewood loam (loamy residuum weathered from sandstone, 2-5% slopes, well-drained, 40-80 inches to paralithic bedrock) and Ramsey loam (loamy residuum weathered from sandstone, 5-12% slopes, somewhat excessively drained) (NRCS, 2014). Initial soil nutrient levels of the experimental site were pH = 5.8, P = 33 kg ha^{-1}, K = 122 kg ha^{-1}, Ca = 2345 kg ha^{-1} and Mg = 117 kg ha^{-1}.

In 2013, three species were tested: switchgrass, sorghum-sudangrass, and bermudagrass. In 2014, crabgrass was added to the experiment, bermudagrass omitted due to winterkill, and both switchgrass and sorghum-sudangrass were tested for a second year. In 2015, bermudagrass and crabgrass were tested for a second year.

Before the experiment began, all vegetation from the perennial plant species was removed and annual plots were tilled and seeded for initial establishment. Switchgrass and bermudagrass plots were previously established in 2008. Due to winterkill during the winter of 2013/2014, bermudagrass was reestablished in May 2014. Sorghum-sudangrass was broadcast seeded at 50.41 kg ha^{-1} on June 6, 2013 and on June 3, 2014. Crabgrass was broadcast seeded at 5.61 kg ha^{-1} on May 27, 2014 and May 20, 2015. Nitrogen fertilizer was applied each year at the rate of 67 kg ha^{-1} to all plots. In 2013, fertilization took place on 5 June for sorghum-sudangrass and on 6 June for switchgrass and bermudagrass. In 2014, switchgrass was fertilized on 6 May, and sorghum-sudangrass and crabgrass on 20 May in 2014. In 2015, bermudagrass and crabgrass were fertilized on 1 May. In all years, annual plots were tilled on the same day they were fertilized.

Three monthly cutting initiations and one height-based cutting regime were imposed on each warm-season perennial species, and two initiation dates and one height-based cutting regime were imposed on each warm-season annual species. In 2013, monthly initiations for switchgrass and bermudagrass were 5 June, 1 July, and 1 August, and for sorghum-sudangrass 1 July and 1 August. In 2014, monthly initiations for switchgrass were 6 June, 1 July, and 1 August, and 1 July and 1 August for sorghum-sudangrass and crabgrass. In 2015, bermudagrass monthly initiations were on 4 June, 6 July, and 3 August and crabgrass monthly initiations were on 13 July, and 3 August.

On each monthly initiation, swards were cut to designated stubble heights, which were selected based on the location of the meristem for each species. Switchgrass and sorghum-sudangrass were cut to 20-cm and bermudagrass and crabgrass were cut to 8-cm. Based on the findings of Burns and Fisher (2008) which determined that maintaining a bermudagrass canopy height above 5 cm results in better animal performance, 8 cm was chosen in our study to be the appropriate sampling and cutting height to support active herbage growth and capture the section of canopy that is most likely to be grazed by cattle in bermudagrass and crabgrass stands. The height-based plots were measured weekly for average sward height and a cut was implemented every time the sward reached its target height as assigned by species. Switchgrass and sorghum-sudangrass were harvested when reaching 76-cm down to 20-cm, while bermudagrass and crabgrass were harvested when reaching 30-cm down to 8-cm. In 2013 height-based cuttings occurred on 5 June, 1 July, 1 August, and 4 September for switchgrass and bermudagrass. For sorghum-sudangrass in 2013 height-based cuttings occurred on 1 July, 1 August, and 4 September. In 2014 height-based cuttings occurred on 6 June, 7 July, 1 August, 14 August, and 9 September for switchgrass. For sorghum-sudangrass and crabgrass in 2014 height-based cuttings occurred on 7 July, 1 August, 14 August, and 9 September In 2015 height-based cutting of bermudagrass occurred on 4 June, 18 June, 6 July, 3 August, and 28 August. In 2015 height-based cutting of crabgrass occurred on 13 July, 3 August, and 28 August.

Measurements

Forage samples were collected weekly from June through July (corresponding to periods of rapid regrowth) and on alternate weeks from August to September (corresponding to periods of slow regrowth) to characterize morphological composition and forage nutritive value. One sample was taken randomly without replacement per experimental unit within a 0.1 m^2 area. The vertical sub-samples were then separated by morphological components (green lamina, dead material, stem+sheath) and dried at 60°C for 72 hours to determine the proportion of each morphological component. Sub-samples were recombined with their corresponding components and (DM) of the whole sample was used to determine HM for the experimental unit before forage nutritive value analysis.

Samples were ground to 1-mm particle size with a Wiley Mill Grinder (Thomas Scientific, Swedesboro, NJ) in preparation for near-infrared spectroscopy (NIRS). Samples were analyzed for multiple quality factors on a DM basis, with CP, acid detergent fiber (ADF), neutral detergent fiber (NDF) and NDFD of particular interest for this experiment, using a FOSS 6500 NIRS instrument (FOSS NIRS, Laurel, MD). Using WINSI II software (Infrasoft International LLC) nutritive value was determined with standardized equations that were checked for accuracy with the equations of the NIRS Forage and Feed Consortium (Hillsboro, WI).

Statistical Analysis

Differences between least squares means for all nutritive value variables and all species were evaluated using the PROC MIXED procedures of SAS (SAS for Windows V 9.4, SAS Institute, Cary, NC). For each analysis, the dependent variable was CP, ADF, NDF, or NDFD. Fixed effects were treatment and stage of maturity (weeks post treatment initiation). Year and rep were random effects. Herbage mass during each initiation date (HM, a dependent variable) was fitted to time (*t*, an independent variable) using the Gompertz equations Eq. [1] with PROC NLIN of SAS (SAS for Windows V 9.4, SAS Institute, Cary, NC) to best fit the data (Nave et al. 2013). Simple regression analysis (PROC REG) in SAS (SAS for Windows V 9.4, SAS Institute, Cary, NC) was used to determine the relationship between three variables of interest, HM and CP, as well as, between HM and NDFD. Differences between least squares means by treatment for morphological composition variables (green-lamina proportion, dead proportion, and stem+sheath proportion) were for tested for each species by year using the PROC MIXED procedures of SAS (SAS for Windows V 9.4, SAS Institute, Cary, NC). For each analysis, the dependent variable was green-lamina proportion, dead proportion, or stem+sheath proportion. Treatment was a fixed effect. Pearson Correlation Coefficients (PROC CORR) were used in SAS (SAS for Windows V 9.4, SAS Institute, Cary, NC) to test existent relationships between forage nutritive value (CP and NDFD) and morphological composition variables (green-lamina proportion, dead proportion, stem+sheath proportion, and HM) for each species by year. All results were evaluated for significance at $P < 0.05$.

RESULTS

Weather

In 2013, June through September temperature was 0.3°C below the 30-yr average. Precipitation in 2013 from June through September was 28% above the 30-yr average (449 mm). In 2014, June through September temperature was 0.7°C above the 30-yr average. Precipitation in 2014 from June through September was 10% higher than the 30-yr average. In 2015, June through September temperature was 0.9°C above the 30-yr average. Precipitation in 2015 from June to September was 69% higher than the 30-yr average (Figure 1.1).

Forage Nutritive Value by Maturity

For switchgrass in both 2013 and 2014 there was a negative trend between CP and date of sampling, with CP decreasing over time (Figure 1.2). The same was observed for switchgrass 2013 and 2014 NDFD (Figure 1.3). For sorghum-sudangrass in both 2013 and 2014 there was a negative trend between CP and date of sampling (Figure 1.4) and NDFD and date of sampling (Figure 1.5). There were also negative trends between CP and date of sampling (Figure 1.6), as well as, NDFD and date of sampling (Figure 1.7) for bermudagrass in both 2013 and 2015. Trends were not clearly distinguishable for crabgrass in either 2014 or 2015 for CP (Figure 1.8) or NDFD (Figure 1.9) by monthly initiations. However, for height-based cuttings there was a negative trend between CP and date of sampling in both 2014 and 2015 crabgrass. In 2015, there was a negative trend between NDFD and date of sampling for height-based cuttings.

When nutritive value variables (CP, ADF, NDF, and NDFD) for monthly initiations and height-based cuttings were compared to one another by maturity (weeks post treatment initiation) and year, nutritive value differed. For switchgrass, differences existed among all variables for monthly initiations (Table 1.1) and height-based cuttings (Table 1.2). For sorghum-sudangrass, differences existed among all variables for monthly initiations (Table 1.3) and height-based cuttings (Table 1.4). For bermudagrass, differences existed among all variables for monthly initiations (Table 1.5) and height-based cuttings (Table 1.6). For crabgrass monthly initiations, differences existed among all variables in 2014, but in 2015 there were no differences in NDF or NDFD (Table 1.7). For crabgrass height-based cuttings, there were no differences in 2014, but in 2015 there were differences in ADF and NDF (Table 1.8).

Herbage Mass Accumulation

Herbage accumulation rate (HAR) was similar between years of each species (Figures 1.10-1.13). In all cases, except for bermudagrass and crabgrass during 2015, HAR decreased with later cutting initiations. Height-based cuttings had similar HARs among cuts, all of which were lower than the HARs of the monthly initiation cuttings.

Relationships of Forage Nutritive Value Factors and Herbage Mass

With the exception of crabgrass, HM predicted CP in at least one year and/or harvest strategy (Figures 1.14-1.19). For switchgrass, CP was negatively affected by HM for monthly initiation cuttings and height-based cuttings in 2013 and 2014. For sorghum-sudangrass, CP was negatively affected by HM for monthly initiation cuttings in 2013 and 2014 and for height-based cuttings in 2013, but in 2014 there was no relationship for height-based cuttings. For bermudagrass there was a negative relationship for monthly initiation cuttings between CP and HM in 2013, but no relationship for 2015. No relationships for monthly initiations or height-based cuttings were found in 2015 for bermudagrass. No relationships were found for crabgrass in either 2014 or 2015. Regression relationships between NDFD and HM were only significant in switchgrass monthly initiations and height-based cuttings during 2013 and 2014.

Morphological Composition

Neither year nor cutting strategy were significant on proportion of green lamina of any species tested, except for bermudagrass during 2015 (Figures 1.20-1.22). Year was not significant on proportion of dead material for any species but cutting strategy was significant in sorghum-sudangrass, bermudagrass, and crabgrass (Figures 1.20-1.22). Year was not significant on proportion of stem+sheath of any species except bermudagrass (Figures 1.20-1.22). Cutting initiation was significant on proportion of stem+sheath material of all species except crabgrass (Figures 1.20-1.22).

Correlations

Results of switchgrass 2013 and 2014 revealed significant correlations between all variables tested except proportion of dead material with proportion of stem and HM. Results of sorghum-sudangrass for 2013 revealed significant correlations between all variables tested with the exception of proportion of dead material, which was not significantly correlated to any variables. However in 2014 sorghum-sudangrass, all variables were significantly correlated except for proportion of dead material with CP, proportion of stem and HM, and proportion of lamina with HM. In both 2013 and 2015, positive relationships existed in bermudagrass for the following variables: CP with NDFD and green lamina; NDFD with green lamina and dead material; green lamina to stem+sheath and dead material; and stem+sheath to HM. For crabgrass in both 2014 and 2015, there was a negative relationship for NDFD to dead material and for stem+sheath to both green lamina and dead material.

DISCUSSION

Values for herbage accumulation were variable among initiation dates and among species, with greater accumulation of HM occurring in June for the warm-season perennials (switchgrass and bermudagrass) (Figures 1.10 and 1.12). Sorghum-sudangrass had greater accumulation occurring in July, while high accumulation of HM for crabgrass occurred in August (Figures 1.11 and 1.13). Barker et al. (2010) studied how the patterns of pasture growth varied with time of year and showed that the initial growth in the season makes it difficult to test the effect of high HM for cool-season grasses. Similarly in our study, most height-based cuttings in all species and the first initiation date of most species (with the exception of bermudagrass in 2015 and crabgrass in both years) could not be accurately estimated due to a very high accumulation rate in the beginning of the growing season.

Differences in CP, ADF, NDF, and NDFD were found among all cutting strategies for all species tested, with the exception of crabgrass (Tables 1.1-1.8). These findings correspond to the patterns observed in cool-season grasses where nutritive value is highest in young herbage regrowth and declines with maturity (Karn et al., 2006; Nave et al., 2014) and to the findings of Beleskey et al. (1991), which reported that CP in bermudagrass steadily decreased with maturity. Bosworth et al. (1980) confirmed the same pattern for crabgrass. Contrarily in our study, CP did not decrease as stands matured and HM increased in crabgrass during 2015 (Table 1.7). This could be attributed to the greater than average rainfall that occurred during the 2015 growing season (Table 1.1), which could have reduced lignification of the stems, thereby maintaining a high CP for longer into the growing season (Griffen and Watson, 1982; Buxton and Fales, 1994;). Values of NDFD varied among cutting strategies and years (Tables 1.1-1.8). In cases where NDFD was different among cutting strategies, NDFD was often greater in the first monthly initiation than in the others, which could be related to the proportions of dead and stem+sheath material, which increased with maturity (Figures 1.20 to 1.22). In all species, the observed ranges of CP, ADF, NDF, and NDFD were comparable to those recorded in other experiments (Bosworth et al., 1980; Griffen and Jung, 1983; Vona et al., 1984; Teutsch et al., 2005; Starks et. al., 2006; Burns and Fisher, 2008; Reich, 2008; Keyser et al., 2011; Temu et al., 2014).

For all species, the morphological proportion of stem+sheath increased as stands matured. As expected, in stands of switchgrass and sorghum-sudangrass, the morphological proportion of green lamina was lowest in mature plots. However, in both bermudagrass and crabgrass mature plots had greater proportions of green lamina and lower proportions of dead material than recently cut plots. In addition, both bermudagrass and crabgrass produced a greater proportion of stem+sheath material than switchgrass and sorghum-sudangrass. This was related to the stoloniferous growing habit of both species (Hirata et al., 2010). When the meristems of these stolons are clipped, lateral growth from the stolon is stimulated rather than upright growth (Younger and McKell, 1972). Hirata et al. (2010) allowed minimum grazing height and morphological composition sampling to occur at 3 cm in their study of stoloniferous warm-season grasses. The results of the study revealed that grazing below a height of 6 cm would cause restriction on animal intake (Hirata et al, 2010). Based on the recommendations of Ball et al. (2007), bermudagrass and crabgrass should be harvested no lower than 2.5 cm to prevent grass injury and promote foliage regrowth. If samples had been collected lower in the canopy strata, different proportions of green lamina, stem+sheath, and dead material may have been observed, capturing a more representative depiction of the plots' regrowth, however it would not be recommended to harvest the plots to such a low height in a grazing system because animal intake could be restricted and in a haymaking situation, uneven ground could result in scalping of the grass stand during harvesting.

In addition, rainfall was greater than average during 2014 and 2015. In a study by Teutsch et al. (2005), which was performed under both conditions of drought and excessive rainfall, HM of crabgrass was significantly influenced by rainfall. Herbage mass was greater under drought, which is attributed to the assumption that during times of excessive rainfall a significant amount of nitrogen was leached from the soil. A similar effect could have occurred in this study.

In mature crabgrass plots, stem+sheath material was high due to the formation of reproductive seed heads. In order to keep stem+sheath proportion low and green lamina proportion high, frequent clipping of seed heads or close grazing may be necessary (Younger and McKell, 1972). Not only does clipping of the seed heads reduce stem+sheath proportion, but it will also stimulate additional production of vegetative tissues. Similar management has been recommended for bermudagrass (Burns et al., 1984).

For switchgrass, bermudagrass, and sorghum-sudangrass, there was a strong positive relationship between CP and proportion of green lamina, a strong negative relationship between CP and proportion of stem+sheath, and a strong negative relationship between CP and HM (Table 1.9). For crabgrass, however, a relationship between CP and morphological components did not exist. There was also no relationship between CP and HM for crabgrass stands. These results could be due to its morphological composition, which changed very little across the season and between management strategies (Figures 1.21 and 1.22). In most cases NDFD was strongly positively correlated with proportion of lamina and strongly negatively correlated with proportion of dead material, proportion of stem+sheath material, and HM. These results correspond with the findings of Nave et al. (2013) that NDFD is highly correlated with NDF, NDFD, and IVTD in cool-season grasses. However, these correlations of NDFD to morphological composition and herbage mass were not consistent with all species in all years. These results led us to believe that HM is a more reliable predictor of CP than NDFD, which is the inverse of similar analysis of cool-season grasses performed by Nave et al. (2013). With adequate moisture, warm-season grasses will have delayed maturity, reduced lignification, and greater regrowth rates than when moisture is inadequate (Buxton and Fales, 1994). The greater than average rainfall and near average seasonal temperatures from 2013 to 2015 supported active growth for much of the growing season, which likely affected the significance of many factors that were examined in this study.

Based on the regression analysis of the relationships between forage nutritive value and HM, it may be possible to predict forage nutritive value from HM for switchgrass and sorghum-sudangrass. Significant linear relationships exist between CP and HM for switchgrass and sorghum-sudangrass. In addition, significant linear relationships were detected between NDFD and HM in switchgrass. In 2013, results from bermudagrass height-based cuttings revealed a significant linear relationship between CP and HM, however no relationship was detected between NDFD and HM. No relationships were detected for bermudagrass in 2015. Results of crabgrass 2014 and 2015 did not yield any relationships between CP or NDFD and HM. Further research should continue to investigate these relationships in bermudagrass and crabgrass.

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CONCLUSIONS

Crude protein and NDFD are important factors for producers to consider when selecting feed for their livestock, with high CP and NDFD being desirable. Therefore, practical ways of estimating CP and NDFD in the field are essential for determining the best time to harvest or graze forage.

After studying the effects of cutting strategies on CP and NDFD, both height-based multiple cuttings or early season single cuts are recommended for all species in this experiment. Nutritive value can significantly decline in August, therefore if using a single cutting harvest technique, harvest should be completed by early July.

Results of this experiment suggest that CP of switchgrass, sorghum-sudangrass, and bermudagrass can be predicted by HM. Herbage mass is a variable that can easily be measured in the field to estimate CP using the regression equations for switchgrass and sorghum-sudangrass developed from this experiment. In addition, CP was highly correlated to the morphological composition of the strata. The greater the proportion of green lamina and the lower the proportion of stem+sheath and dead material the greater the CP content of the forage. These observations could offer assistance to producers making decisions based on visual estimates.

In this experiment, NDFD was not reliably predicted by HM in any species examined. However, our results suggest that switchgrass may exhibit a significant relationship between NDFD and HM in future studies. Additionally, results of this study did not indicate significant relationships between CP and HM in the case of crabgrass, which we suspect was due to the lack of change in morphological composition across the season and grass canopy sampling height. Further research should be conducted on crabgrass investigating these relationships to confirm whether relationships are truly non-existent.

APPENDIX A

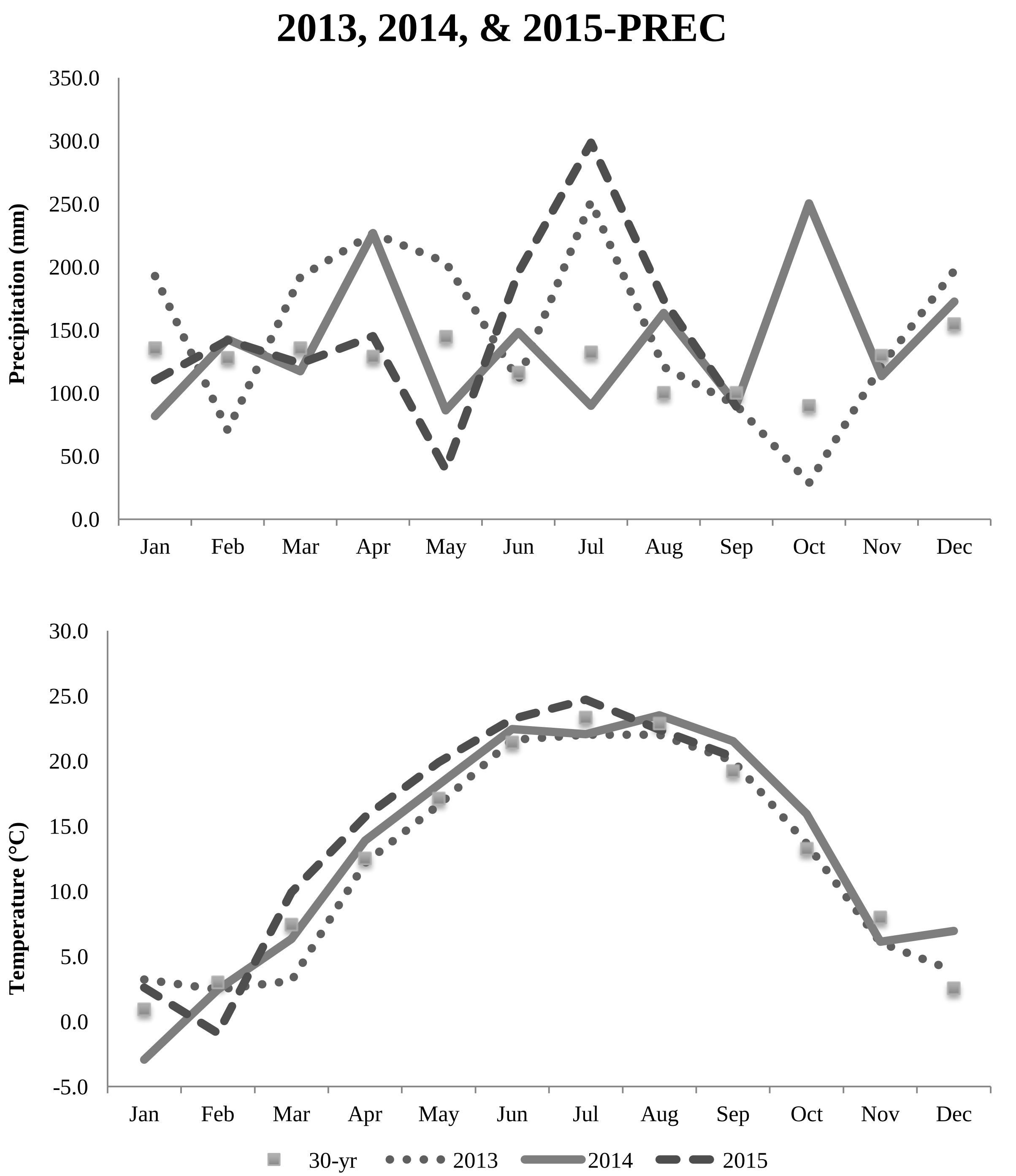


Figure 1.1. Weather for Plateau AgResearch and Education Center, Crossville, TN, 2013-2015 including 30-year average.

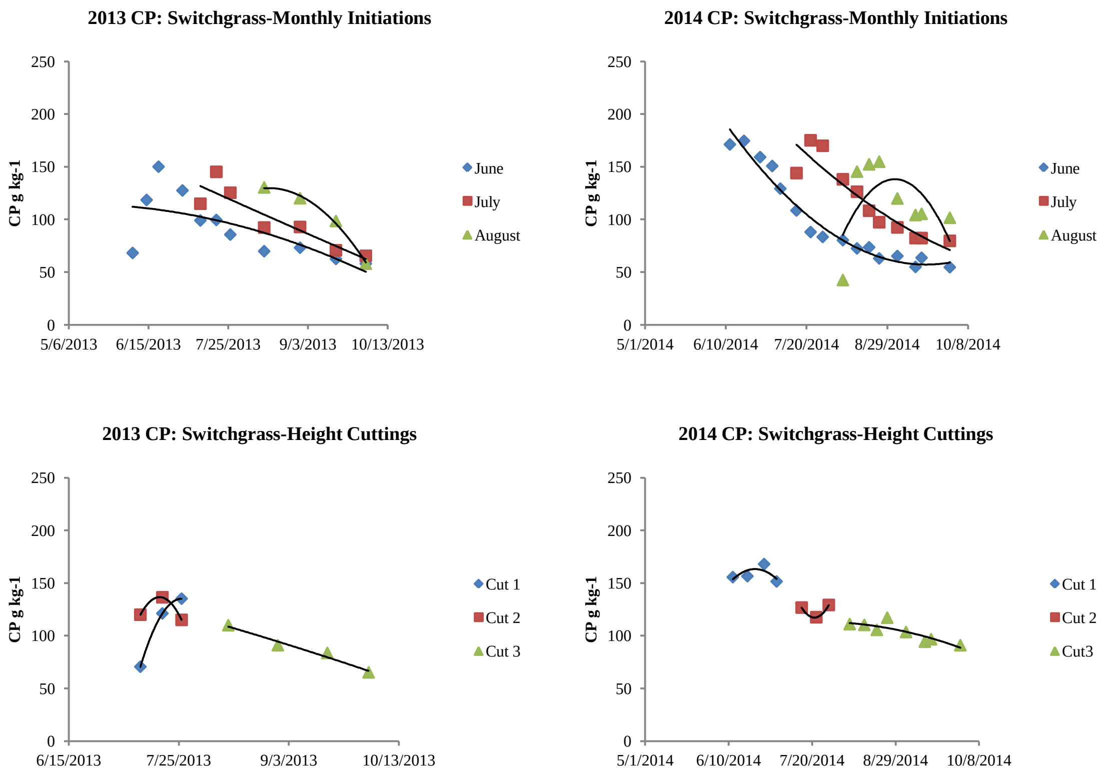


Figure 1.2. Crude protein (CP) of switchgrass observed by sampling date at Plateau AgResearch and Education Center, Crossville, TN, during the 2013 and 2014 growing seasons.

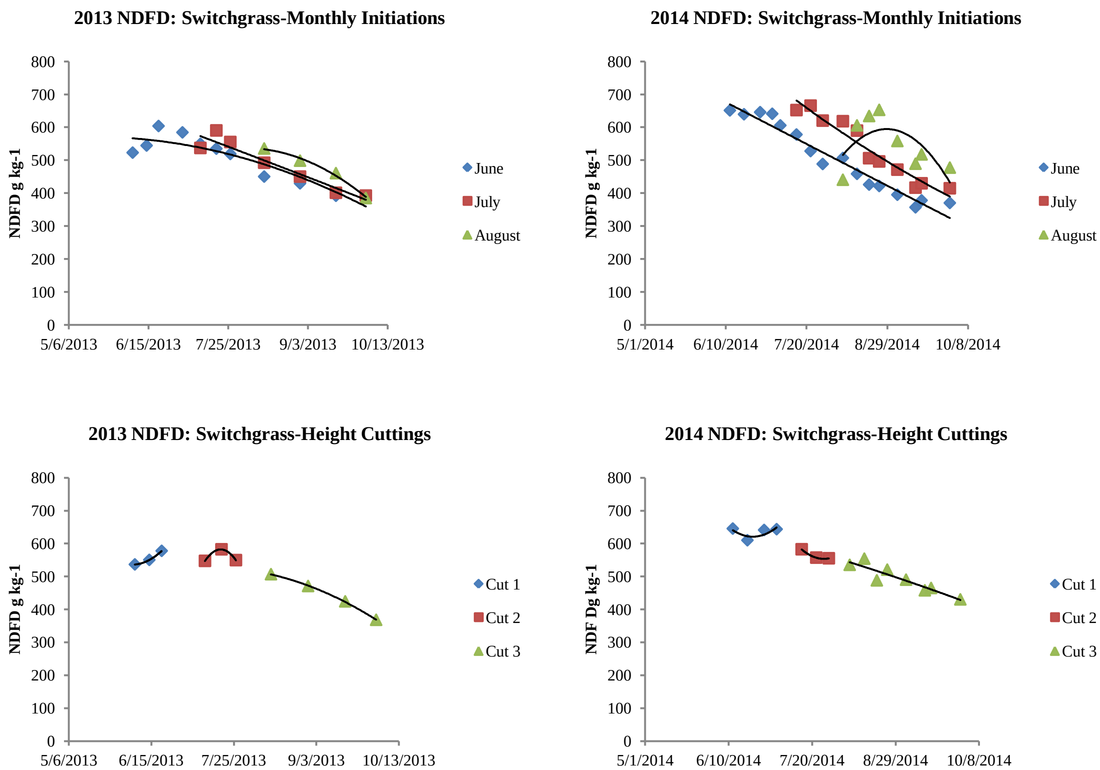


Figure 1.3. Neutral detergent fiber digestibility (NDFD) of switchgrass observed by sampling date at Plateau AgResearch and Education Center, Crossville, TN, during the 2013 and 2014 growing seasons.

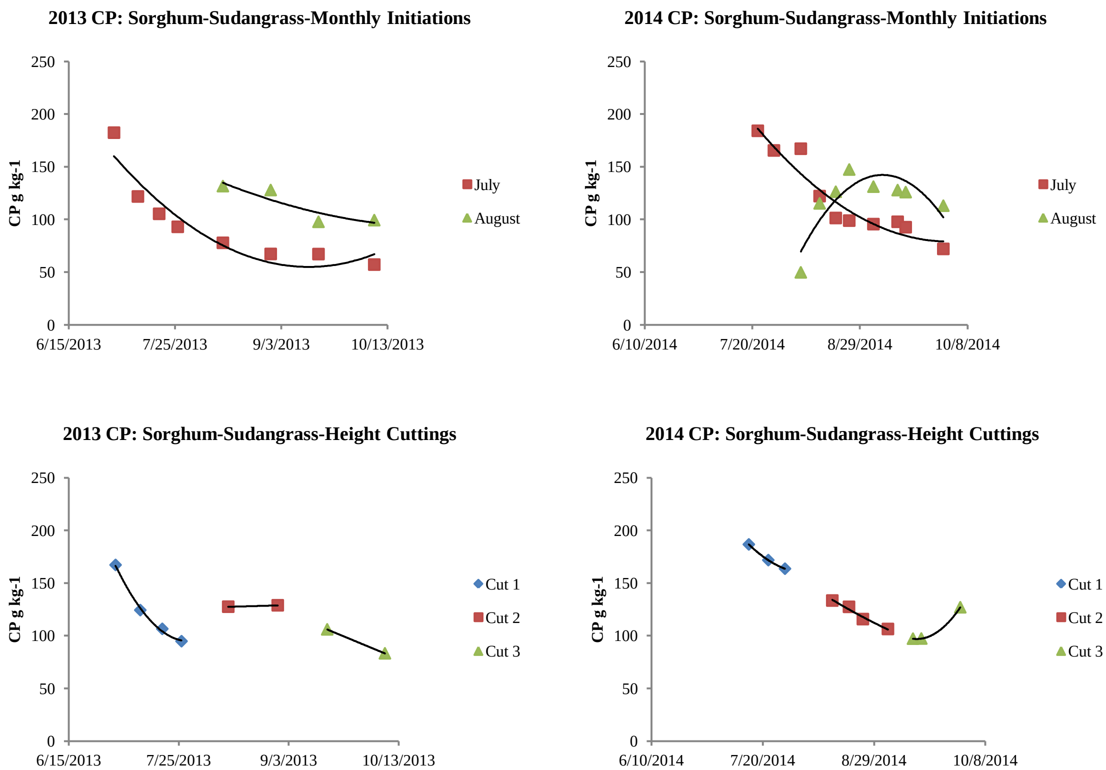


Figure 1.4. Crude protein (CP) of sorghum-sudangrass observed by sampling date at Plateau AgResearch and Education Center, Crossville, TN, during the 2013 and 2014 growing seasons.

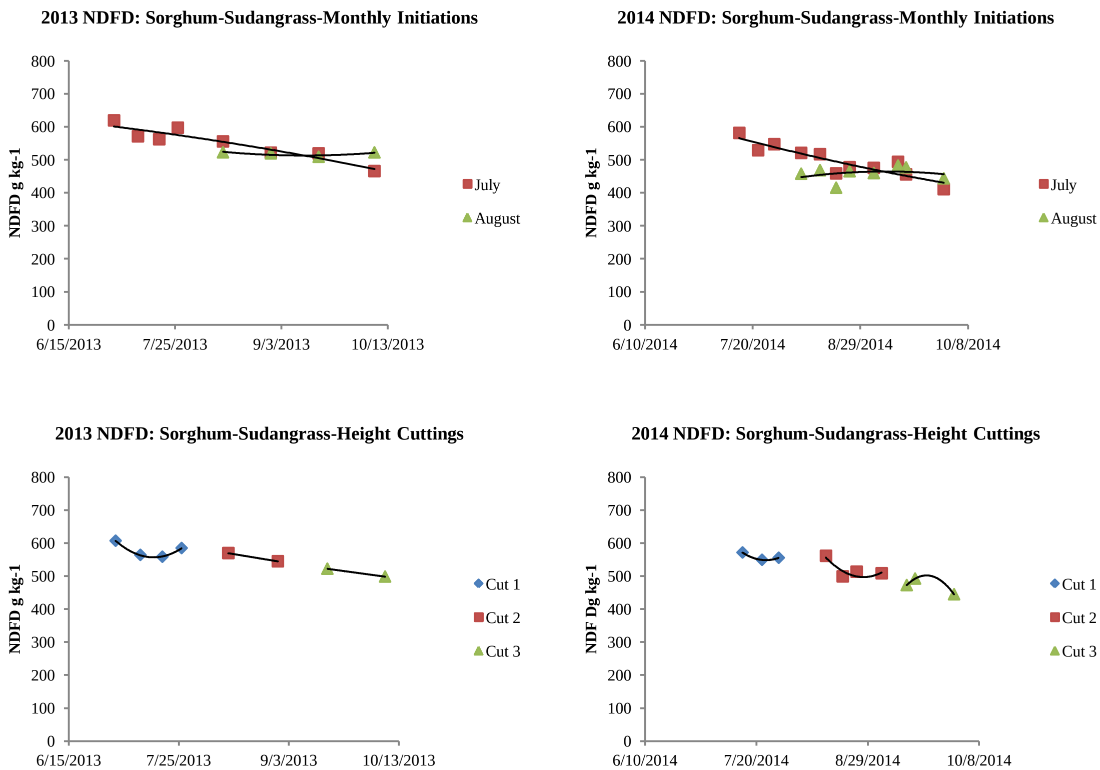


Figure 1.5. Neutral detergent fiber digestibility (NDFD) of sorghum-sudangrass observed by sampling date at Plateau AgResearch and Education Center, Crossville, TN, during the 2013 and 2014 growing seasons.

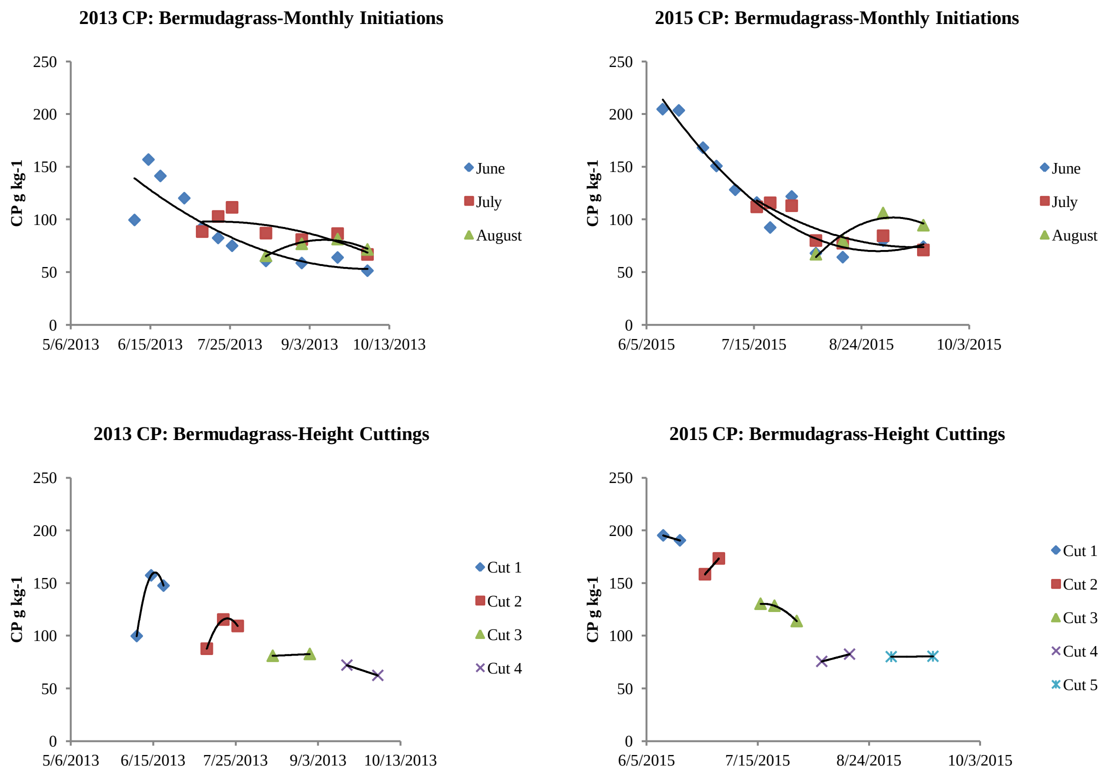


Figure 1.6. Crude protein (CP) of bermudagrass observed by sampling date at Plateau AgResearch and Education Center, Crossville, TN, during the 2013 and 2015 growing seasons.

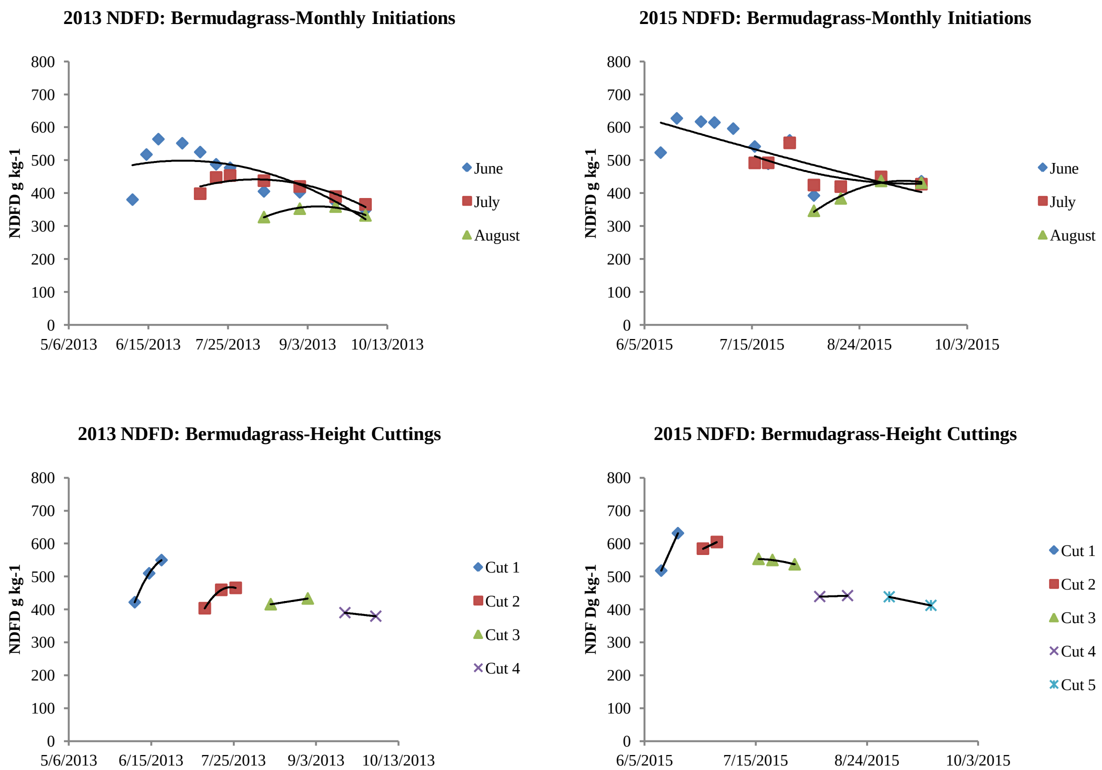


Figure 1.7. Neutral detergent fiber digestibility (NDFD) of bermudagrass observed by sampling date at Plateau AgResearch and Education Center, Crossville, TN, during the 2013 and 2015 growing seasons.

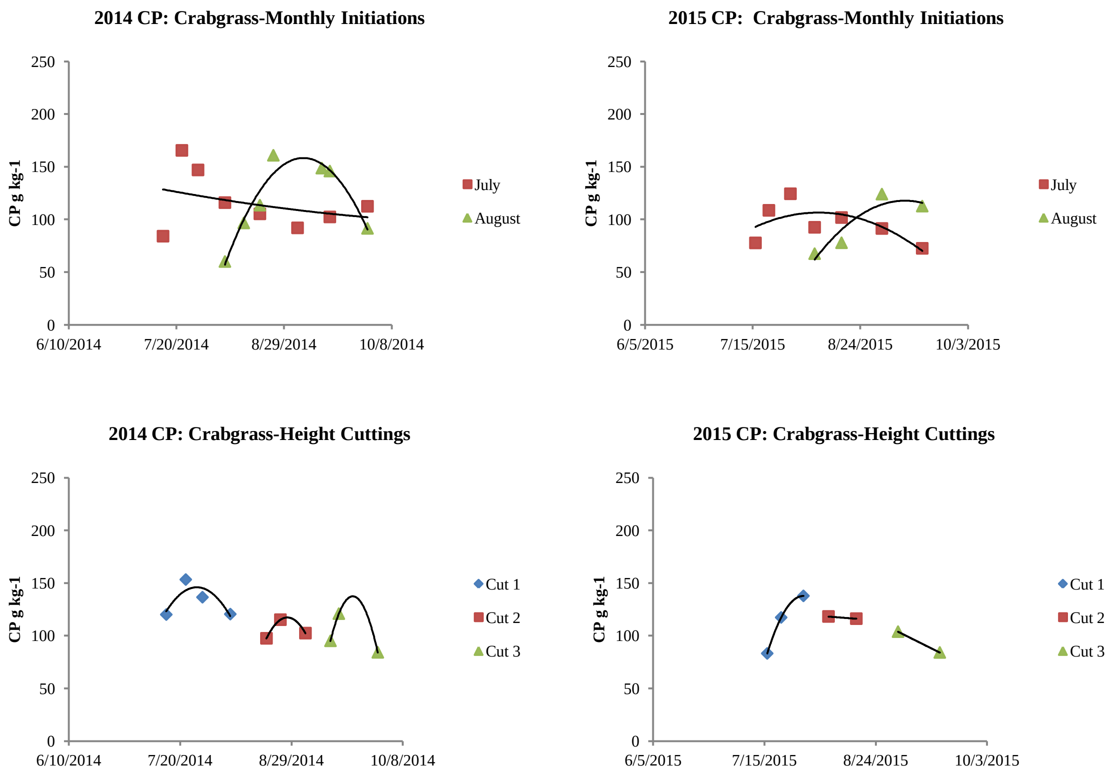


Figure 1.8. Crude protein (CP) of crabgrass observed by sampling date at Plateau AgResearch and Education Center, Crossville, TN, during the 2014 and 2015 growing seasons.

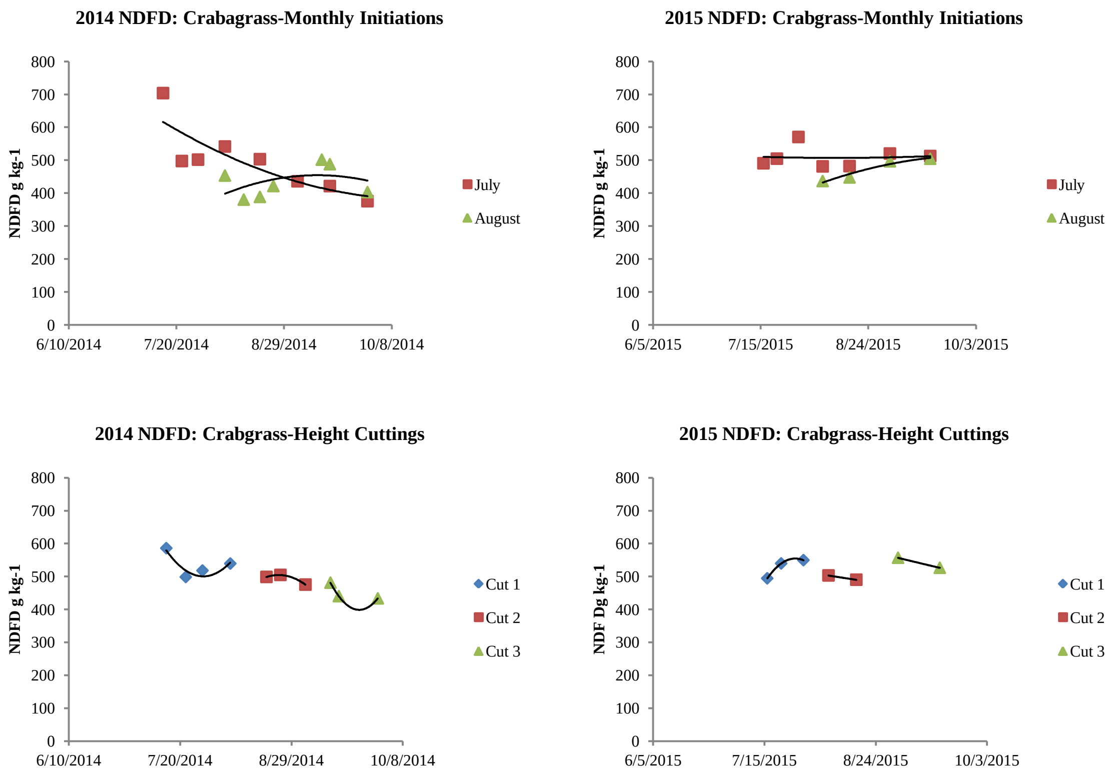


Figure 1.9. Neutral detergent fiber digestibility (NDFD) of crabgrass observed by sampling date at Plateau AgResearch and Education Center, Crossville, TN, during the 2014 and 2015 growing seasons.

Table 1.1. Nutritive value of switchgrass monthly initiations by maturity during the 2013 and 2014 growing seasons at Plateau AgResearch and Education Center, Crossville, TN.

	2013 Switchgrass					**2014 Switchgrass**			
	Weeks Post Treatment Initiation					**Weeks Post Treatment Initiation**			
	2	**4**	**6**	**8**		**2**	**4**	**6**	**8**
	‡CP g kg^{-1}					**‡CP g kg^{-1}**			
June	118.50^{a}	127.49^{a}	98.31^{a}	69.80^{a}	**June**	174.57^{a}	150.71^{a}	108.48^{a}	83.38^{b}
July	145.15^{a}	92.30^{b}	92.82^{a}	70.68^{a}	**July**	175.08^{a}	138.05^{b}	108.24^{a}	92.42^{ab}
August	130.32^{a}	120.14^{ab}	98.47^{a}	85.32^{a}	**August**	145.38^{a}	154.74^{a}	104.18^{a}	101.56^{a}
P	0.0654	0.0248	0.4457	0.0304	***P***	0.4435	0.0003	0.7752	0.0153
	‡ADF g kg^{-1}					**‡ADF g kg^{-1}**			
June	405.91^{a}	377.43^{b}	414.37^{b}	474.50^{a}	**June**	345.93^{a}	367.36^{a}	406.15^{b}	444.01^{a}
July	387.15^{a}	436.40^{a}	456.95^{a}	481.70^{a}	**July**	327.82^{a}	367.99^{a}	417.14^{b}	440.46^{a}
August	374.62^{a}	422.43^{ab}	437.86^{ab}	459.86^{a}	**August**	415.88^{a}	373.10^{a}	440.32^{a}	423.98^{a}
P	0.0831	0.0155	0.0124	0.1197	***P***	0.1849	0.5413	0.0058	0.2851
	‡NDF g kg^{-1}					**‡NDF g kg^{-1}**			
June	620.67^{a}	599.93^{b}	647.14^{a}	711.31^{a}	**June**	519.06^{a}	557.31^{b}	632.54^{a}	656.86^{a}
July	586.93^{ab}	661.14^{a}	682.48^{a}	717.97^{a}	**July**	485.44^{a}	574.65^{a}	618.21^{a}	659.31^{a}
August	558.06^{b}	634.38^{ab}	659.13^{a}	695.52^{a}	**August**	611.72^{a}	569.47^{ab}	634.30^{a}	633.42^{a}
P	0.0252	0.0646	0.0646	0.2122	***P***	0.1136	0.0216	0.3545	0.1283
	‡NDFD g kg^{-1}					**‡NDFD g kg^{-1}**			
June	544.44^{ab}	584.440^{a}	533.06^{a}	450.17^{a}	**June**	639.38^{a}	640.93^{a}	577.94^{a}	488.44^{a}
July	590.29^{a}	492.21^{b}	450.13.^{b}	400.91^{b}	**July**	665.65^{a}	618.35^{a}	506.03^{b}	471.24^{a}
August	535.53^{b}	498.55^{b}	460.64^{b}	420.06^{ab}	**August**	605.65^{a}	652.89^{a}	489.28^{b}	477.44^{b}
P	0.0390	0.0019	0.0010	0.0360	***P***	0.658	0.1422	0.0004	0.4010

Means within a column without a common superscript letter differ ($P < 0.05$).

‡ CP, crude protein; ADF, acid detergent fiber; NDF neutral detergent fiber; NDFD, neutral detergent fiber digestibility

Table 1.2. Nutritive value of switchgrass height based cuttings by maturity during the 2013 and 2014 growing seasons at Plateau AgResearch and Education Center, Crossville, TN.

2013 Switchgrass				**2014 Switchgrass**				
Weeks Post Treatment Initiation				**Weeks Post Treatment Initiation**				
	1	**2**	**3**		**1**	**2**	**3**	**4**
		‡CP g kg^{-1}				**‡CP g kg^{-1}**		
Cut 1	70.45^{b}	121.06^{ab}	135.09^{a}	**Cut 1**	155.49^{a}	156.37^{a}	167.87^{a}	151.39^{a}
Cut 2	119.85^{a}	136.36^{a}	114.93^{b}	**Cut 2**	126.60^{a}	117.45^{b}	129.08^{ab}	.
Cut 3	.	109.84^{b}	.	**Cut 3**	110.18^{a}	110.18^{b}	105.44^{b}	116.96.^{b}
P	0.0003	0.0082	0.0059	***P***	0.0985	0.0089	0.013	0.0163
		‡ADF g kg^{-1}				**‡ADF g kg^{-1}**		
Cut 1	445.36^{a}	395.50^{a}	380.59^{b}	**Cut 1**	393.30^{a}	367.92^{a}	358.57^{b}	369.82^{b}
Cut 2	402.36^{b}	389.59^{a}	108.90^{a}	**Cut 2**	399.44^{a}	401.71^{a}	397.24^{ab}	.
Cut 3	.	396.37^{a}	.	**Cut 3**	433.53^{a}	404.04^{a}	425.58^{a}	411.18^{a}
P	0.0444	0.8048	0.0252	***P***	0.0472	0.0718	0.0487	0.0156
		‡NDF g kg^{-1}				**‡NDF g kg^{-1}**		
Cut 1	678.48^{a}	607.73^{a}	590.83^{a}	**Cut 1**	585.83^{a}	540.90^{b}	547.22^{b}	560.82^{b}
Cut 2	608.34^{b}	602.53^{a}	628.19^{a}	**Cut 2**	606.03^{a}	606.43^{a}	596.86^{ab}	.
Cut 3	.	594.50^{a}	.	**Cut 3**	641.73^{a}	624.50^{a}	636.04^{a}	631.22^{a}
P	0.0124	0.7145	0.0064	***P***	0.1833	0.0067	0.0323	0.0085
		‡NDFD g kg^{-1}				**‡NDFD g kg^{-1}**		
Cut 1	536.33^{a}	550.09^{a}	577.49^{a}	**Cut 1**	645.15^{a}	609.71^{a}	640.87^{a}	643.32$^{a.}$
Cut 2	547.06^{a}	582.11^{a}	549.30^{a}	**Cut 2**	582.29^{ab}	556.96^{a}	544.92^{b}	.
Cut 3	.	506.58^{b}	.	**Cut 3**	534.99^{b}	553.80^{a}	487.87^{b}	520.44^{b}
P	0.4144	0.0018	0.1730	***P***	0.0481	0.1135	0.0017	0.0026

Means within a column without a common superscript letter differ ($P < 0.05$).
‡ CP, crude protein; ADF, acid detergent fiber; NDF neutral detergent fiber; NDFD, neutral detergent fiber digestibility

Table 1.3. Nutritive value of sorghum-sudangrass monthly initiations by maturity during the 2013 and 2014 growing seasons at Plateau AgResearch and Education Center, Crossville, TN.

2013 Sorghum-Sudangrass					2014 Sorghum-Sudangrass				
Weeks Post Treatment Initiation					**Weeks Post Treatment Initiation**				
	2	**4**	**6**	**8**		**2**	**4**	**6**	**8**
		‡CP g kg^{-1}					**‡CP g kg^{-1}**		
July	115.95^{a}	92.98^{b}	77.77^{b}	69.99^{b}	**July**	165.46^{a}	122.12^{a}	98.87^{b}	97.75^{a}
August	131.62^{a}	127.89^{a}	97.73^{a}	97.73^{a}	**August**	115.22^{b}	147.37^{a}	127.85^{a}	113.05^{a}
P	0.0589	0.0065	0.0065	0.0304	***P***	0.0284	0.2722	0.0248	0.2028
		‡ADF g kg^{-1}					**‡ADF g kg^{-1}**		
July	424.57^{a}	442.89^{a}	461.75^{a}	464.47^{b}	**July**	358.42^{b}	396.41^{a}	447.17^{a}	453.88^{a}
August	458.62^{a}	416.85^{b}	442.97^{b}	427.40^{a}	**August**	480.34^{a}	454.46^{a}	457.75^{a}	455.04^{a}
P	0.2436	0.036	0.0016	0.049	***P***	0.0100	0.1098	0.4927	0.9285
		‡NDF g kg^{-1}					**‡NDF g kg^{-1}**		
July	630.84^{a}	665.22^{a}	696.30^{a}	701.83^{a}	**July**	537.20^{b}	604.67^{a}	656.61^{a}	696.73^{a}
August	627.15^{a}	599.55^{b}	654.56^{b}	658.71^{b}	**August**	688.40^{a}	656.32^{a}	676.62^{a}	663.04^{a}
P	0.9152	0.0032	0.0111	0.0098	***P***	0.0113	0.2270	0.2981	0.0747
		‡NDFD g kg^{-1}					**‡NDFD g kg^{-1}**		
July	564.65^{a}	597.25^{a}	555.59^{a}	521.52^{a}	**July**	528.90^{a}	520.87^{a}	458.69^{a}	475.33^{a}
August	522.61^{a}	519.37^{b}	509.17^{b}	522.37^{a}	**August**	468.41^{a}	465.24^{a}	482.58^{a}	443.72^{b}
P	0.1564	<0.0001	0.0003	0.9674	***P***	0.0928	0.0854	0.2705	0.0253

Means within a column without a common superscript letter differ ($P < 0.05$).

‡ CP, crude protein; ADF, acid detergent fiber; NDF neutral detergent fiber; NDFD, neutral detergent fiber digestibility

Table 1.4. Nutritive value of sorghum-sudangrass height based cuttings by maturity during the 2013 and 2014 growing seasons at Plateau AgResearch and Education Center, Crossville, TN.

	2013 Sorghum-Sudangrass					**2014 Sorghum-Sudangrass**			
	Weeks Post Treatment Initiation					**Weeks Post Treatment Initiation**			
	1	**2**	**3**	**4**		**1**	**2**	**3**	**4**
	‡CP g kg^{-1}					**‡CP g kg^{-1}**			
Cut 1	167.07	124.21^{a}	106.44	94.69^{b}	**Cut 1**	186.56^{a}	171.67^{a}	163.51^{a}	122.04^{a}
Cut 2	.	135.13^{a}	.	128.79^{a}	**Cut 2**	133.30^{b}	127.32^{ab}	115.66^{b}	106.27^{a}
Cut 3	.	105.93^{a}	.	83.19^{b}	**Cut 3**	97.13^{b}	97.23^{b}	.	126.90^{a}
P	.	0.4202	.	0.0023	***P***	0.0006	0.0144	0.0018	0.2828
	‡ADF g kg^{-1}					**‡ADF g kg^{-1}**			
Cut 1	328.83	403.70^{a}	457.52	447.10^{a}	**Cut 1**	342.00^{c}	351.30^{b}	360.34^{b}	405.81^{b}
Cut 2	.	414.85^{a}	.	400.82^{b}	**Cut 2**	389.31^{b}	420.61^{ab}	423.70^{a}	432.95^{ab}
Cut 3	.	426.01^{a}	.	447.06^{a}	**Cut 3**	500.13^{a}	488.19^{a}	.	457.66^{a}
P	.	0.7853	.	0.0002	***P***	<0.0001	0.0212	0.0003	0.0391
	‡NDF g kg^{-1}					**‡NDF g kg^{-1}**			
Cut 1	502.98	598.55^{a}	675.05	661.13^{a}	**Cut 1**	510.02^{c}	524.33^{b}	539.02^{b}	608.33^{a}
Cut 2	.	574.58^{a}	.	582.38^{b}	**Cut 2**	600.69^{b}	620.19^{ab}	638.10^{a}	657.47^{a}
Cut 3	.	642.84^{a}	.	666.66^{a}	**Cut 3**	722.82^{a}	704.24^{a}	.	659.44^{a}
P	.	0.3623	.	<0.0001	***P***	<0.0001	0.0122	<0.0001	0.0854
	‡NDFD g kg^{-1}					**‡NDFD g kg^{-1}**			
Cut 1	606.94	563.98^{a}	558.45	584.70^{a}	**Cut 1**	571.25^{a}	549.07^{a}	555.26^{a}	535.57^{a}
Cut 2	.	574.93^{a}	.	544.62^{a}	**Cut 2**	561.13^{a}	498.67^{a}	513.04^{a}	508.12^{a}
Cut 3	.	522.15^{a}	.	498.33^{b}	**Cut 3**	472.45^{b}	492.17^{a}	.	444.61^{b}
P	.	0.0418	.	0.0012	***P***	0.0066	0.2105	0.1745	0.0056

Means within a column without a common superscript letter differ (P < 0.05).
‡ CP, crude protein; ADF, acid detergent fiber; NDF neutral detergent fiber; NDFD, neutral detergent fiber digestibility

Table 1.5. Nutritive value of bermudagrass monthly initiations by maturity during the 2013 and 2015 growing seasons at Plateau AgResearch and Education Center, Crossville, TN.

2013 Bermudagrass					**2015 Bermudagrass**				
Weeks Post Treatment Initiation					**Weeks Post Treatment Initiation**				
	2	**4**	**6**	**8**		**2**	**4**	**6**	**8**
‡CP g kg^{-1}					**‡CP g kg^{-1}**				
June	156.80^{a}	120.20^{a}	82.40^{a}	75.00^{b}	**June**	203.48^{a}	150.72^{a}	116.06^{a}	88.68^{a}
July	102.80^{b}	111.50^{a}	87.00^{a}	80.90^{a}	**July**	115.77^{b}	79.95^{b}	77.41^{a}	84.49^{a}
August	65.50c	76.90^{b}	81.40^{a}	71.50^{ab}	**August**	79.60^{b}	106.12^{b}	94.50^{a}	.
P	0.0002	0.0026	0.2774	0.0110	***P***	<0.0001	0.0007	0.0793	0.6258
‡ADF g kg^{-1}					**‡ADF g kg^{-1}**				
June	360.98^{c}	352.30^{c}	393.55^{b}	426.80^{b}	**June**	291.35^{b}	342.95^{b}	367.77^{b}	348.92^{b}
July	421.33^{b}	405.53^{b}	395.70^{b}	405.15^{b}	**July**	407.60^{a}	424.53^{a}	439.44^{a}	420.24^{a}
August	485.80^{a}	459.78^{a}	452.20^{a}	472.43^{a}	**August**	438.25^{a}	416.50^{a}	408.85^{ab}	.
P	<0.0001	<0.0001	0.0003	0.0004	***P***	<0.0001	0.0028	0.0042	0.0135
‡NDF g kg^{-1}					**‡NDF g kg^{-1}**				
June	586.55^{c}	582.35^{c}	623.46^{a}	656.78^{b}	**June**	505.33^{b}	576.14^{b}	577.62^{b}	551.10^{b}
July	654.98^{b}	640.97^{b}	621.33^{b}	629.45^{c}	**July**	623.72^{a}	628.02^{a}	648.65^{a}	631.35^{a}
August	716.58^{a}	686.80^{a}	678.88^{a}	710.95^{a}	**August**	634.64^{a}	651.95^{a}	634.04^{a}	.
P	<0.0001	0.0002	0.0007	<0.0001	***P***	0.0003	0.0013	0.0061	0.006
‡NDFD g kg^{-1}					**‡NDFD g kg^{-1}**				
June	517.15^{a}	551.48^{a}	487.43^{a}	405.13^{a}	**June**	627.01^{a}	614.45^{a}	541.48^{a}	509.89^{a}
July	447.50^{b}	446.73^{b}	437.58^{b}	420.13^{a}	**July**	491.87^{b}	424.44^{b}	419.67^{b}	449.19^{a}
August	327.10^{c}	352.70^{c}	359.10^{c}	332.18^{b}	**August**	383.86^{b}	436.92^{b}	431.81^{b}	.
P	<0.0001	<0.0001	0.0001	0.0003	***P***	0.0007	<0.0001	0.0007	0.098

Means within a column without a common superscript letter differ ($P < 0.05$).

‡ CP, crude protein; ADF, acid detergent fiber; NDF neutral detergent fiber; NDFD, neutral detergent fiber digestibility

Table 1.6. Nutritive value of bermudagrass height based cuttings by maturity during the 2013 and 2015 growing seasons at Plateau AgResearch and Education Center, Crossville, TN.

	2013 Bermudagrass					**2015 Bermudagrass**		
	Weeks Post Treatment Initiation					**Weeks Post Treatment Initiation**		
	1	**2**	**3**	**4**		**1**	**2**	**3**
	‡CP g kg^{-1}					**‡CP g kg^{-1}**		
Cut 1	104.14^{a}	157.20^{a}	147.43^{a}	.	**Cut 1**	195.15^{a}	190.43^{a}	.
Cut 2	87.57^{a}	115.28^{b}	109.13^{b}	.	**Cut 2**	158.28^{b}	173.26^{a}	.
Cut 3	.	80.90^{c}	.	82.60^{a}	**Cut 3**	130.28^{c}	128.41^{b}	113.86^{a}
Cut 4	.	72.00^{c}	.	62.28^{a}	**Cut 4**	75.54^{d}	.	82.42^{b}
P	0.1106	<0.0001	0.0094	0.0669	***P***	<0.0001	0.0036	0.0008
	‡ADF g kg^{-1}					**‡ADF g kg^{-1}**		
Cut 1	427.26^{a}	361.38^{b}	350.60^{b}	.	**Cut 1**	318.98^{b}	306.08^{b}	.
Cut 2	439.90^{a}	416.82^{a}	408.63^{a}	.	**Cut 2**	338.42^{b}	328.37^{b}	.
Cut 3	.	412.58^{a}	.	399.48^{b}	**Cut 3**	360.34^{b}	375.97^{a}	367.75^{b}
Cut 4	.	419.95^{a}	.	430.95^{a}	**Cut 4**	412.32^{a}	.	440.09^{a}
P	0.4332	0.0016	0.0092	0.0205	***P***	0.0002	0.0006	0.0164
	‡NDF g kg^{-1}					**‡NDF g kg^{-1}**		
Cut 1	653.56^{a}	580.90^{b}	577.68^{b}	.	**Cut 1**	524.59^{b}	523.09^{b}	.
Cut 2	660.80^{a}	643.40^{a}	639.85^{a}	.	**Cut 2**	572.33^{a}	563.51^{a}	.
Cut 3	.	636.95^{a}	.	615.30^{b}	**Cut 3**	575.96^{a}	585.75^{a}	561.74^{b}
Cut 4	.	651.13^{a}	.	664.35^{a}	**Cut 4**	599.13^{a}	.	638.27^{a}
P	0.7294	0.0032	0.0115	0.0122	***P***	0.0026	0.0038	0.0041
	‡NDFD g kg^{-1}					**‡NDFD g kg^{-1}**		
Cut 1	421.36^{a}	509.23^{a}	549.38^{a}	.	**Cut 1**	517.40^{ab}	631.11^{a}	.
Cut 2	403.20^{a}	459.03^{ab}	465.03^{b}	.	**Cut 2**	584.05^{a}	604.22^{ab}	.
Cut 3	.	415.40^{bc}	.	432.90^{a}	**Cut 3**	553.18^{a}	549.85^{b}	536.72^{a}
Cut 4	.	389.75^{c}	.	379.05^{b}	**Cut 4**	438.66^{b}	.	441.50^{b}
P	0..4441	0.0005	0.0391	0.0186	***P***	0.0011	0.0186	0.0078

Means within a column without a common superscript letter differ ($P < 0.05$).
‡ CP, crude protein; ADF, acid detergent fiber; NDF neutral detergent fiber; NDFD, neutral detergent fiber digestibility

Table 1.7. Nutritive value of crabgrass monthly initiations by maturity during the 2014 and 2015 growing seasons at Plateau AgResearch and Education Center, Crossville, TN.

	2014 Crabgrass					**2015 Crabgrass**		
	Weeks Post Treatment Initiation					**Weeks Post Treatment Initiation**		
	2	**4**	**6**	**8**		**2**	**4**	**6**
	‡CP g kg^{-1}					**‡CP g kg^{-1}**		
July	165.52^{a}	115.95^{a}	105.30^{b}	91.98^{a}	**July**	108.63^{a}	92.52^{b}	101.80^{a}
August	96.66^{b}	160.88^{a}	148.7^{a}	98.56^{a}	**August**	77.86^{b}	124.02^{a}	112.63^{a}
P	0.0031	0.0854	0.0499	0.6748	***P***	0.0040	0.0422	0.4076
	‡ADF g kg^{-1}					**‡ADF g kg^{-1}**		
July	385.82^{b}	385.82^{a}	430.59^{a}	443.11^{a}	**July**	456.48^{a}	437.18^{a}	465.39^{a}
August	501.30^{a}	433.48^{a}	411.98^{a}	466.66^{a}	**August**	499.79^{a}	410.99^{b}	418.70^{a}
P	0.0051	0.2586	0.4796	0.6873	***P***	0.2270	0.0174	0.0976
	‡NDF g kg^{-1}					**‡NDF g kg^{-1}**		
July	544.01^{b}	569.17^{a}	623.20^{a}	601.97^{a}	**July**	657.92^{a}	625.92^{a}	651.86^{a}
August	671.82^{a}	601.96^{a}	585.44^{a}	622.34^{a}	**August**	688.83^{a}	619.65^{a}	634.56^{a}
P	0.0047	0.4283	0.1423	0.7218	***P***	0.4094	0.6970	0.5147
	‡NDFD g kg^{-1}					**‡NDFD g kg^{-1}**		
July	497.35^{a}	541.52^{a}	503.01^{a}	435.89^{a}	**July**	504.60^{a}	481.03^{a}	481.94^{a}
August	380.32^{b}	421.46^{b}	501.52^{a}	403.00^{a}	**August**	447.40^{a}	496.53^{a}	504.33^{a}
P	0.0038	0.0035	0.9757	0.3275	***P***	0.1314	0.6654	0.3281

Means within a column without a common superscript letter differ ($P < 0.05$).
‡ CP, crude protein; ADF, acid detergent fiber; NDF neutral detergent fiber; NDFD, neutral detergent fiber digestibility

Table 1.8. Nutritive value of crabgrass height based cuttings by maturity during the 2015 growing season at Plateau AgResearch and Education Center, Crossville, TN.

2015 Crabgrass			
Weeks Post Treatment Initiation			
	1	**2**	**3**
‡CP g kg^{-1}			
Cut 1	83.11^{a}	117.23^{a}	123.54^{a}
Cut 2	118.17^{a}	.	116.10^{a}
Cut 3	.	103.79^{a}	.
P	0.0545	0.22	0.6599
‡ADF g kg^{-1}			
Cut 1	485.25^{a}	459.55^{a}	385.11^{b}
Cut 2	456.44^{a}	.	453.80^{a}
Cut 3	.	408.39^{b}	.
P	0.5156	0.0321	0.0406
‡NDF g kg^{-1}			
Cut 1	690.72^{a}	638.08^{a}	545.92^{b}
Cut 2	635.86^{a}	.	633.72^{a}
Cut 3	.	594.26^{a}	.
P	0.2350	0.1538	0.0245
‡NDFD g kg^{-1}			
Cut 1	493.98^{a}	539.31^{a}	536.26^{a}
Cut 2	502.79^{a}	.	489.82^{a}
Cut 3	.	556.52^{a}	.
P	0.8422	0.7328	0.1033

Means within a column without a common superscript letter differ ($P < 0.05$).
‡ CP, crude protein; ADF, acid detergent fiber; NDF neutral detergent fiber; NDFD, neutral detergent fiber digestibility

Table 1.9. Simple correlations between CP, NDFD, proportion of lamina, proportion of dead, proportion of stem, and HM across all management strategies, for four harvest timing experiments during 2013, 2014, and 2015 at Plateau AgResearch and Education Center, Crossville, TN.

Species	Year	‡CP to ‡NDFD	CP to Lamina	CP to Dead	CP to Stem	CP to ‡HM
Switchgrass	2013	0.8562*	0.8598*	-0.4593*	-0.8131*	-0.7175*
	2014	0.9424*	0.8606*	-0.0928	-0.8757*	-0.6993*
Sorghum-Sudangrass	2013	0.6509*	0.8829*	-0.0036	-0.9085*	-0.7837*
	2014	0.6711*	0.6967*	-0.2920	-0.6742*	-0.5150*
Bermudagrass	2013	0.7838*	0.8748*	-0.3345	-0.6818*	0.3856*
	2015	0.8366*	0.6972*	-0.6149*	-0.1614	-0.3163
Crabgrass	2014	0.1029	0.2371	-0.2133	-0.0174	-0.0910
	2015	0.5769*	0.8100*	-0.1909	-0.5664*	-0.3629

Species	Year	NDFD to Lamina	NDFD to Dead	NDFD to Stem	NDFD to HM	Lamina to Dead
Switchgrass	2013	0.8006*	-0.6474*	-0.6786*	-0.6988*	-0.5163*
	2014	0.8255*	-0.0487	-0.8975*	-0.6993*	-0.5099*
Sorghum-Sudangrass	2013	0.6995*	-0.4078	-0.5515*	-0.4716*	-0.2741
	2014	0.7021*	-0.6051*	-0.3714*	-0.4705*	-0.6915*
Bermudagrass	2013	0.7973*	-0.7034*	-0.3053	0.5959*	-0.4664*
	2015	0.7382*	-0.8120*	0.0731	-0.0897	0.7905*
Crabgrass	2014	0.8154*	-0.4882*	-0.2772	-0.2777	-0.1314
	2015	0.4435	-0.4723*	-0.0615	0.0393	-0.1673

Species	Year	Lamina to Stem	Lamina to HM	Dead to Stem	Dead to HM	Stem to HM
Switchgrass	2013	-0.9521*	-0.8075*	0.2295	0.3050	0.8087
	2014	-0.7110*	-0.5850*	-0.2243	-0.1682	0.8257*
Sorghum-Sudangrass	2013	-0.9167*	-0.7817*	-0.1329	-0.0880	0.8422*
	2014	-0.6977*	-0.3005	-0.0350	-0.1673	0.5817*
Bermudagrass	2013	-0.7121*	0.5524*	-0.2881	-0.4627*	-0.2311
	2015	0.3703*	-0.2840	-0.2762	-0.1224	0.6314*
Crabgrass	2014	-0.6557*	-0.3974*	-0.6328*	-0.3883*	0.6608*
	2015	-0.7455*	-0.2570	-0.5324*	-0.0251	0.2376

*** Significant at *P* < 0.05**

‡ CP, crude protein; NDFD, neutral detergent fiber digestibility; HM, herbage mass.

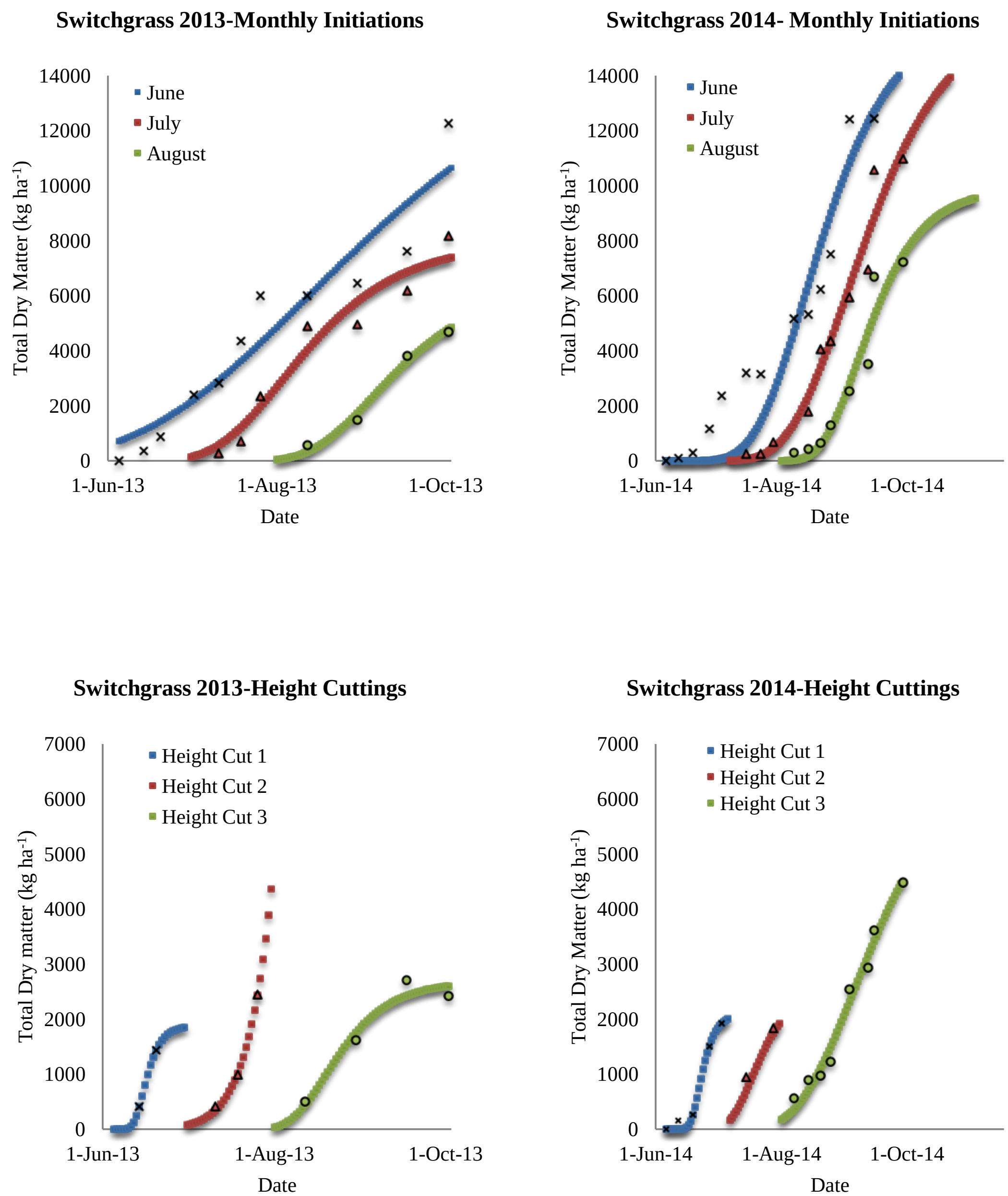


Figure 1.10. Estimated herbage accumulation rates of switchgrass by management strategy during the 2013 and 2014 growing seasons at Plateau AgResearch and Education Center, Crossville, TN.

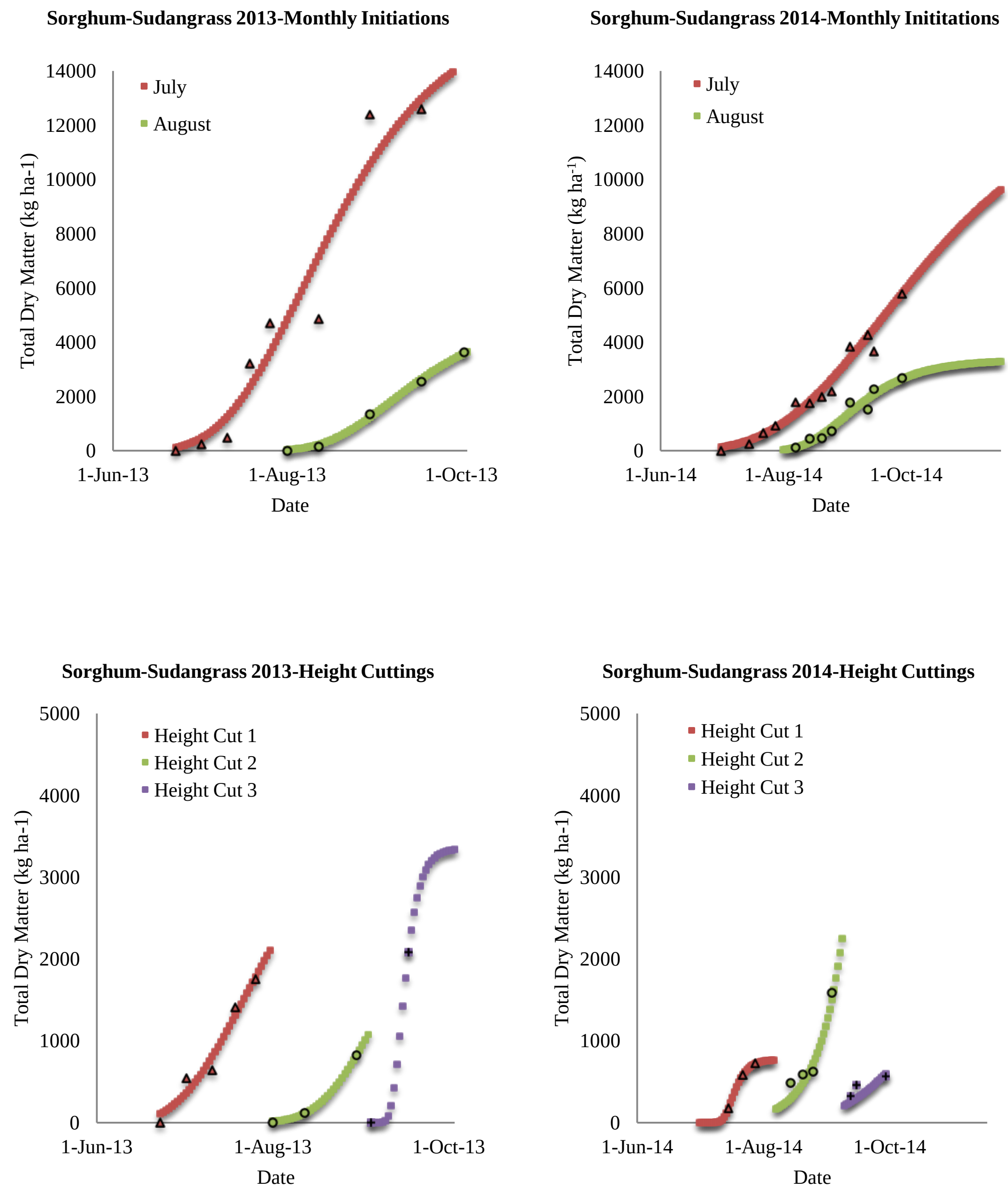


Figure 1.11. Estimated herbage accumulation rates of sorghum-sudangrass by management strategy during the 2013 and 2014 growing seasons at Plateau AgResearch and Education Center, Crossville, TN.

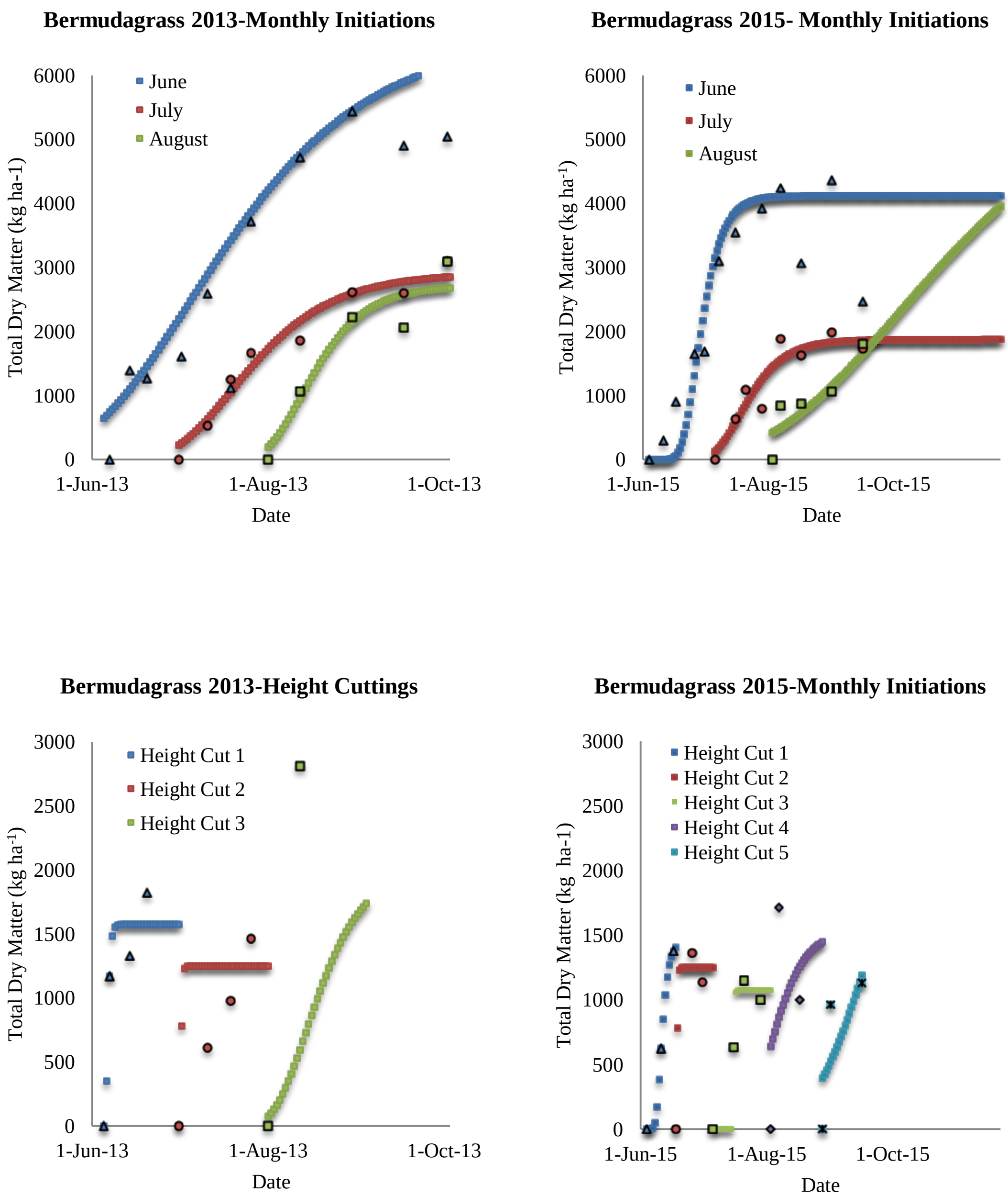


Figure 1.12. Estimated herbage accumulation rates of bermudagrass by management strategy during the 2013 and 2015 growing seasons at Plateau AgResearch and Education Center, Crossville, TN.

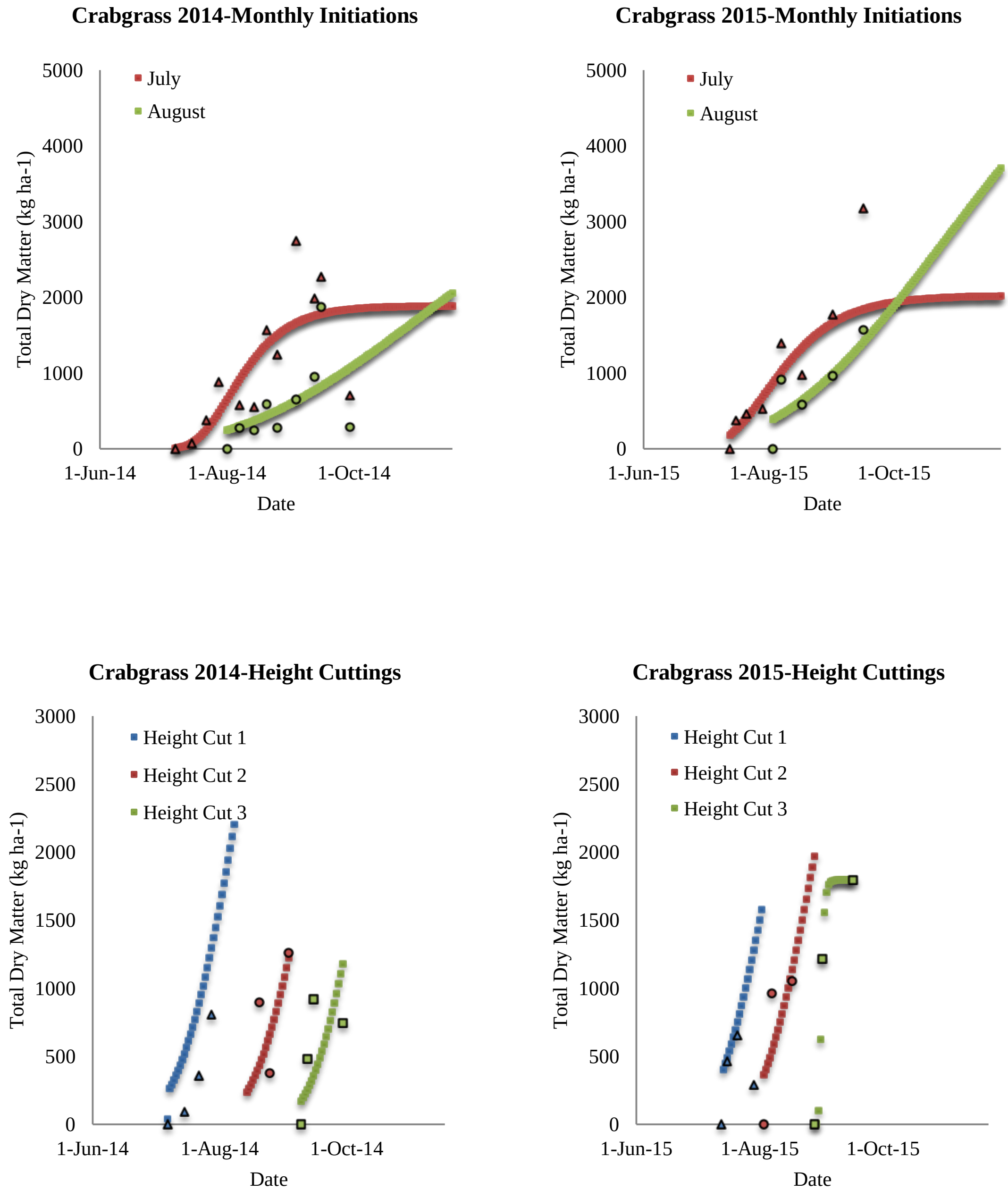


Figure 1.13. Estimated herbage accumulation rates of crabgrass by management strategy during the 2014 and 2015 growing seasons at Plateau AgResearch and Education Center, Crossville, TN.

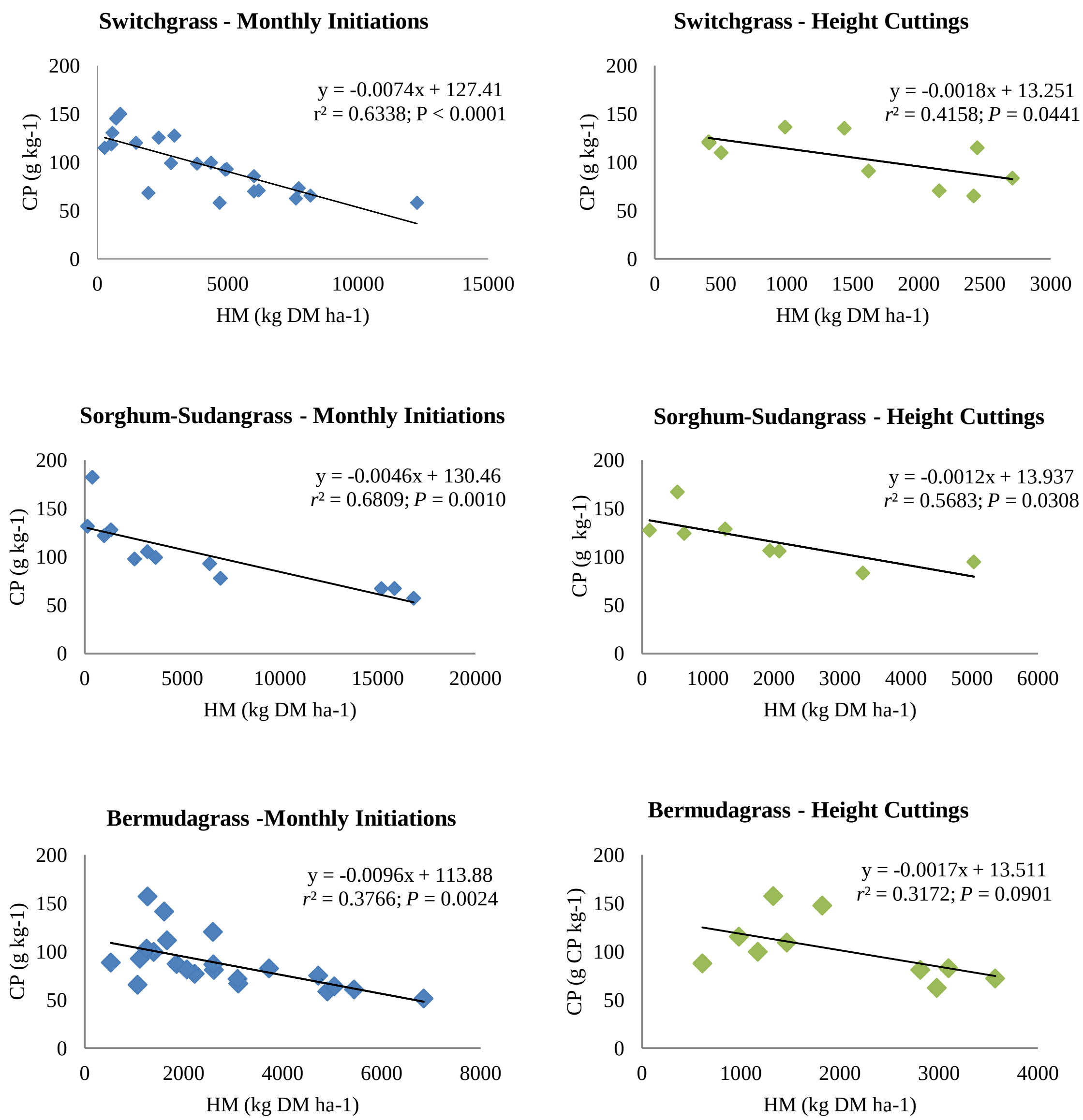


Figure 1.14. Relationship between crude protein (CP) and herbage mass (HM) for monthly initiations (June, July, and August) and height based cutting of switchgrass, sorghum-sudangrass and bermudagrass across the 2013 growing season at Plateau AgResearch and Education Center, Crossville, TN.

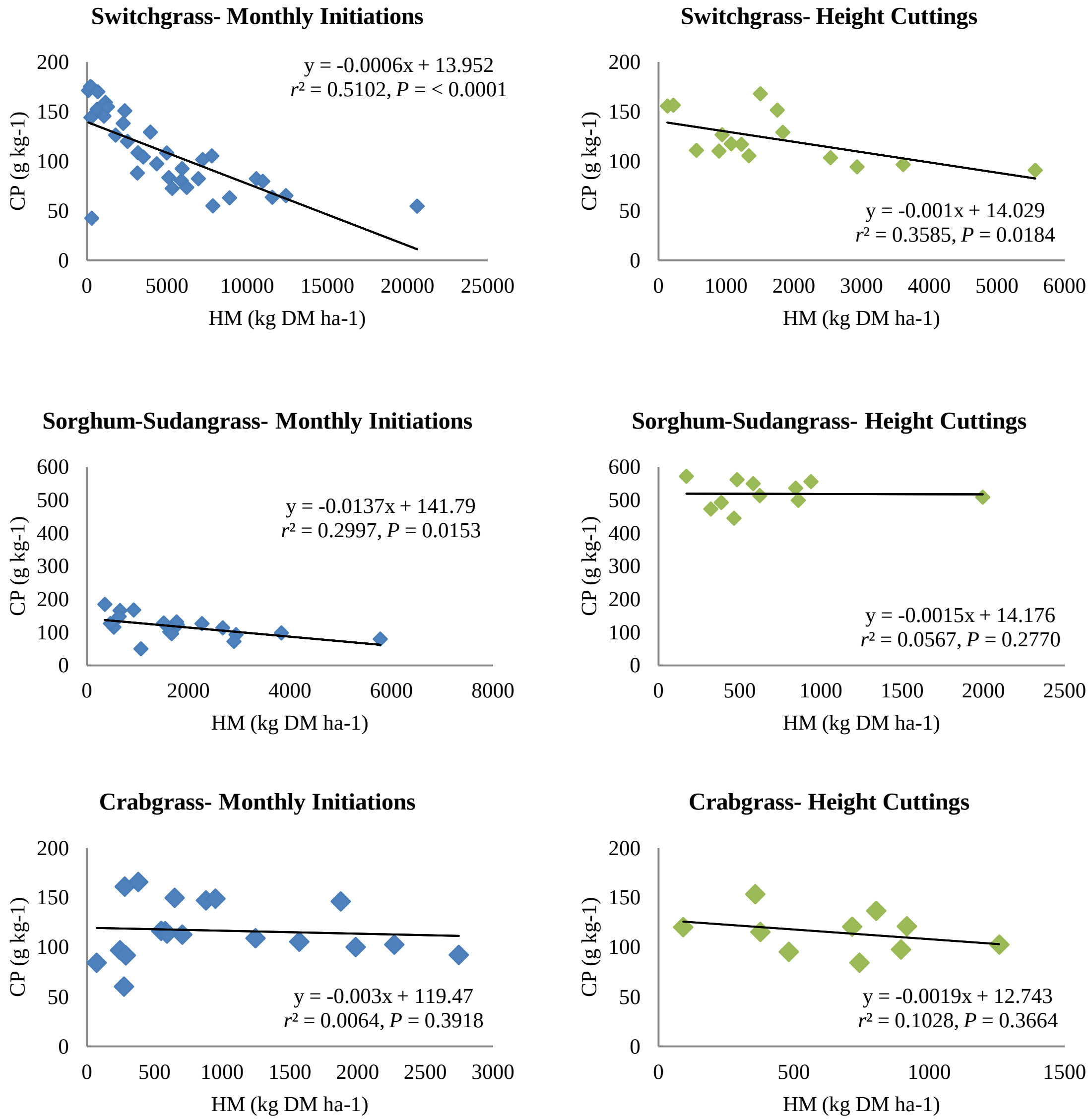


Figure 1.15. Relationship between crude protein (CP) and herbage mass (HM) for monthly initiations (June, July, and August) and height based cutting of switchgrass, sorghum-sudangrass and crabgrass across the 2014 growing season at Plateau AgResearch and Education Center, Crossville, TN.

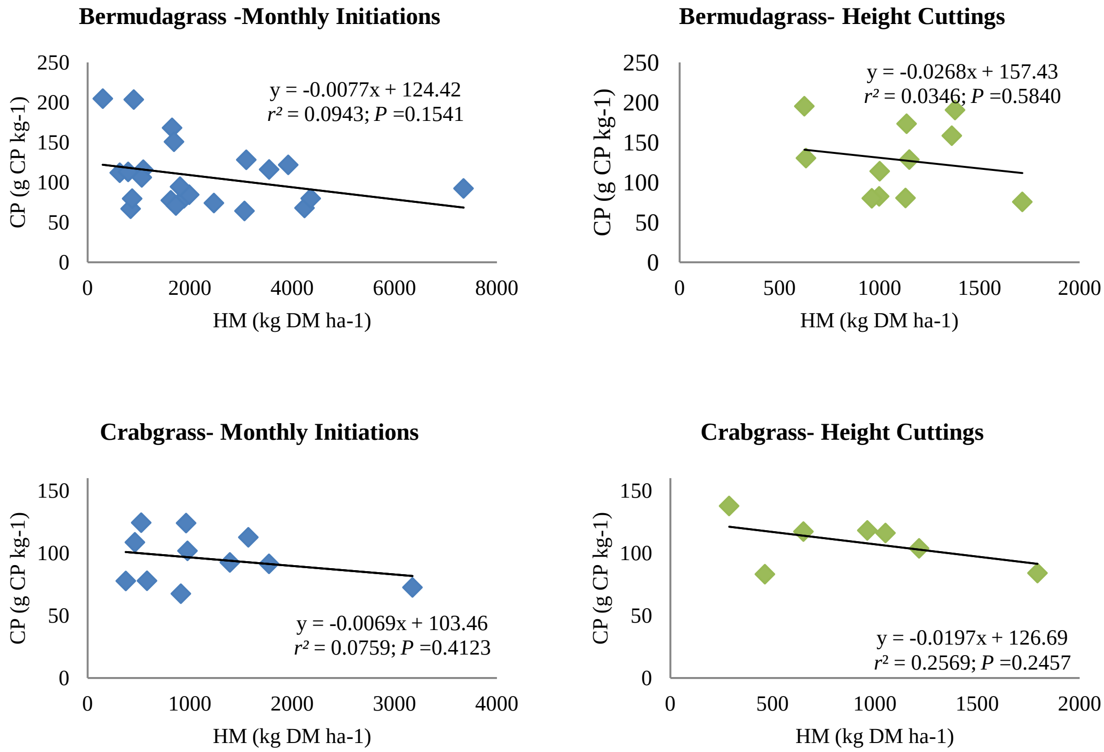


Figure 1.16. Relationship between crude protein (CP) and herbage mass (HM) for monthly initiations (June, July, and August) and height based cutting of bermudagrass and crabgrass across the 2015 growing season at Plateau AgResearch and Education Center, Crossville, TN.

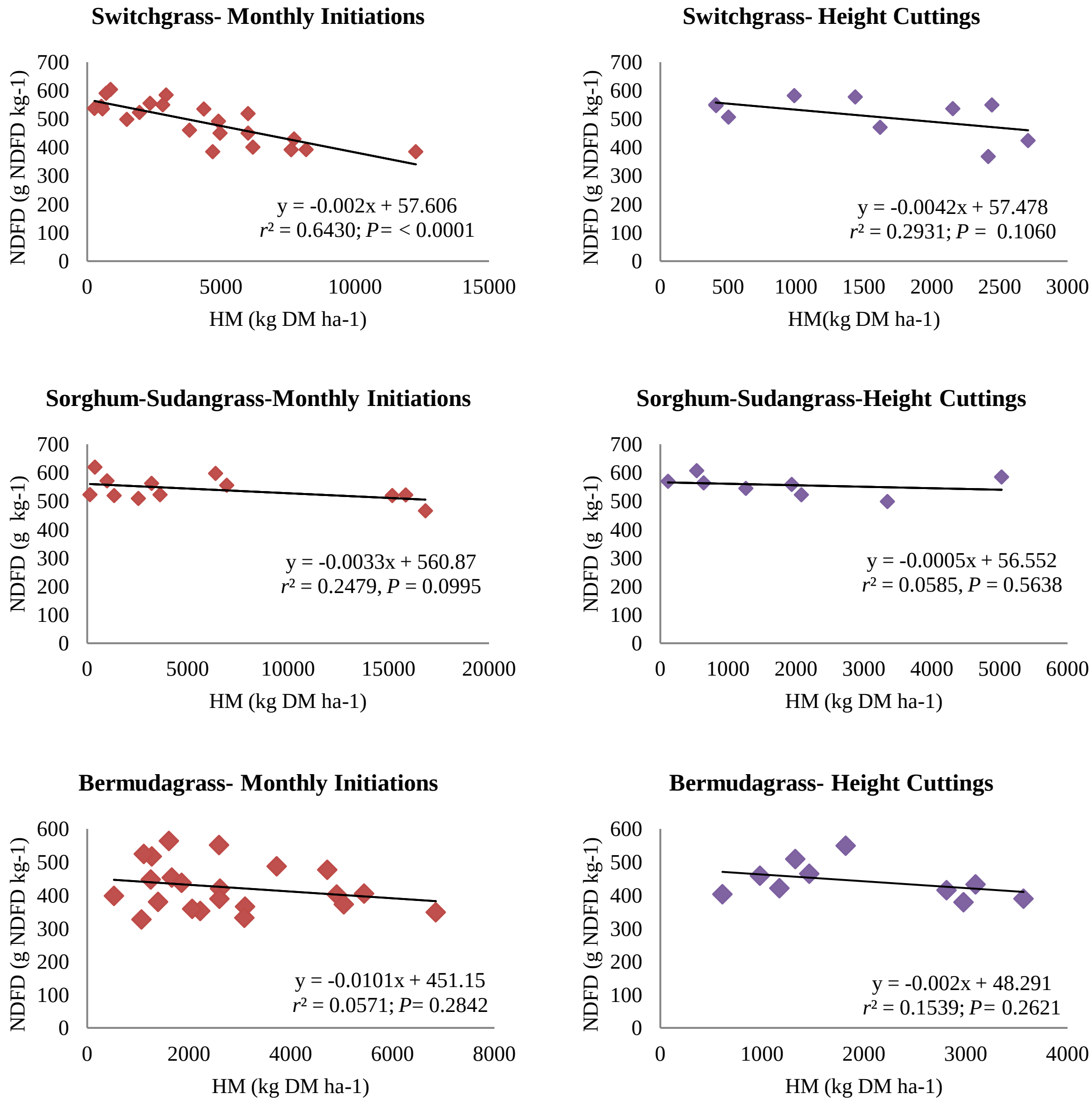


Figure 1.17. Relationship between neutral detergent fiber digestibility (NDFD) and herbage mass (HM) for monthly initiations (June, July, and August) and height based cutting of switchgrass, sorghum-sudangrass and bermudagrass across the 2013 growing season at Plateau AgResearch and Education Center, Crossville, TN.

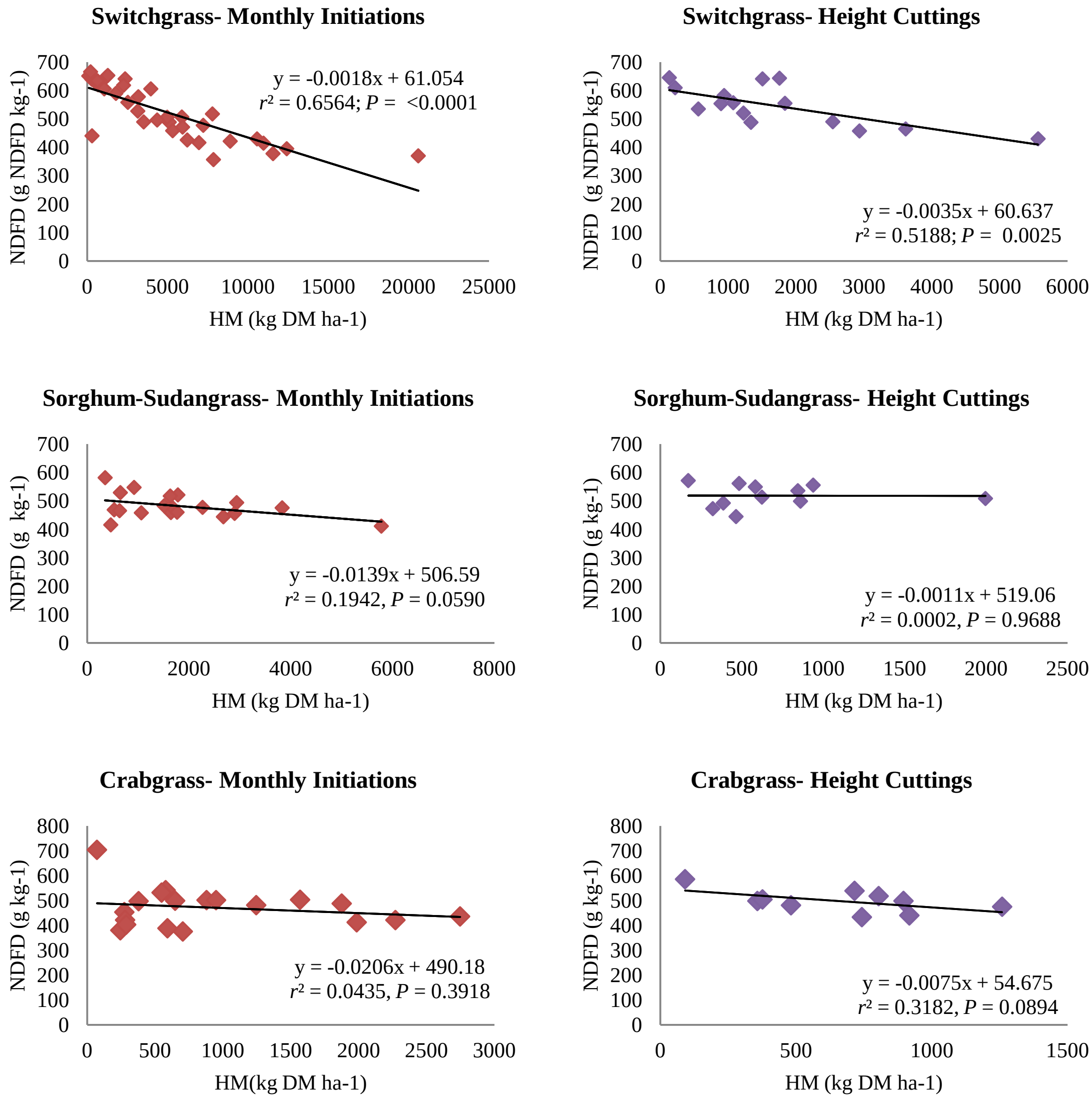


Figure 1.18. Relationship between neutral detergent fiber digestibility (NDFD) and herbage mass (HM) for monthly initiations (June, July, and August) and height based cutting of switchgrass, sorghum-sudangrass and crabgrass across the 2014 growing season at Plateau AgResearch and Education Center, Crossville, TN.

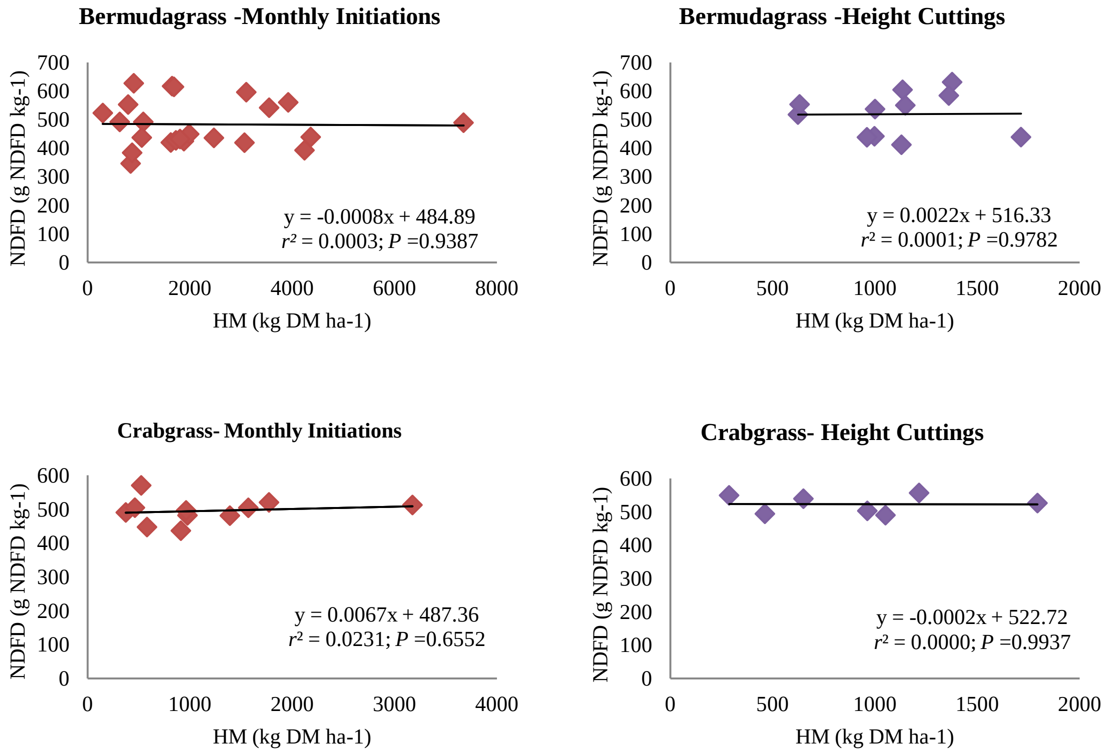
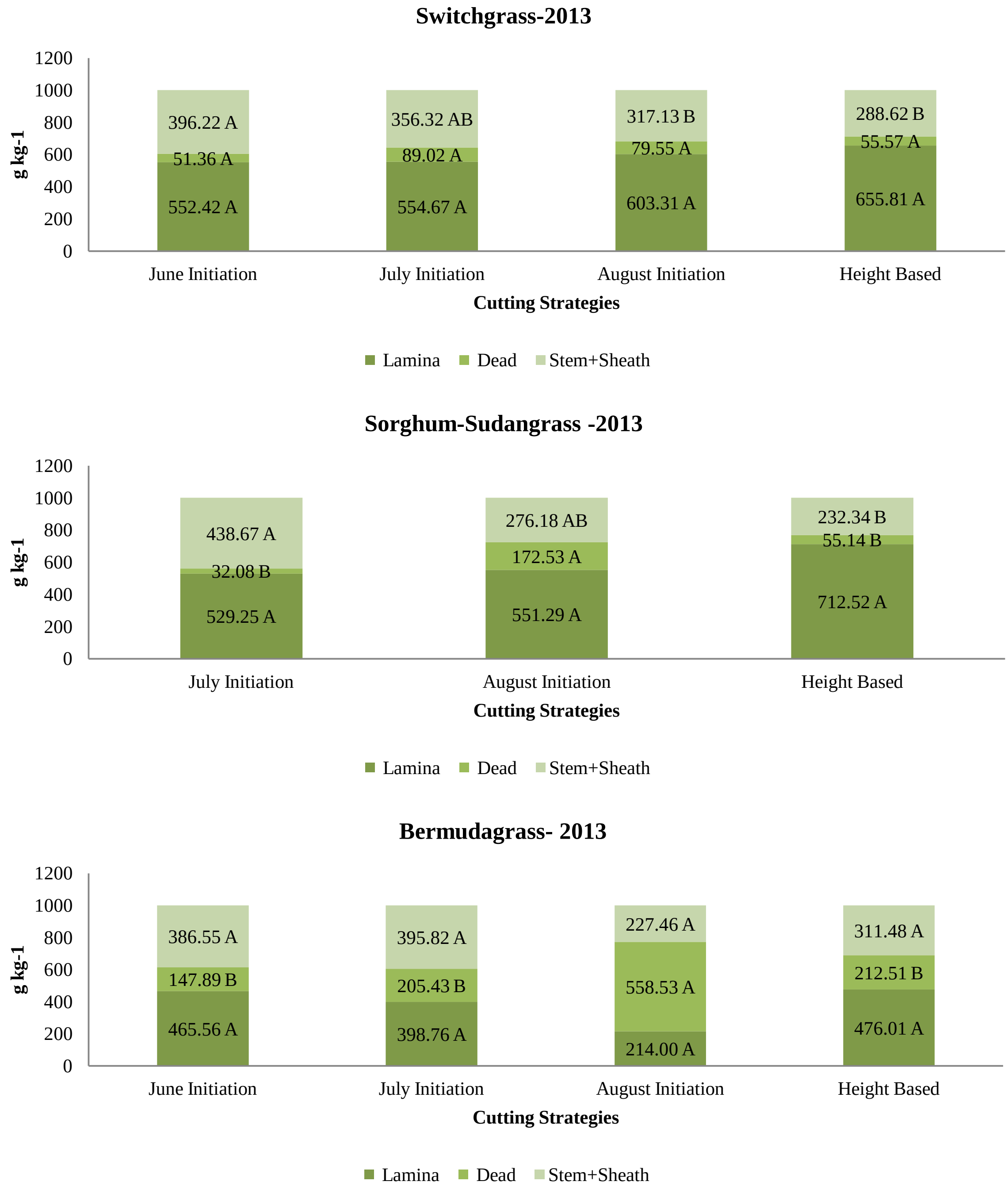
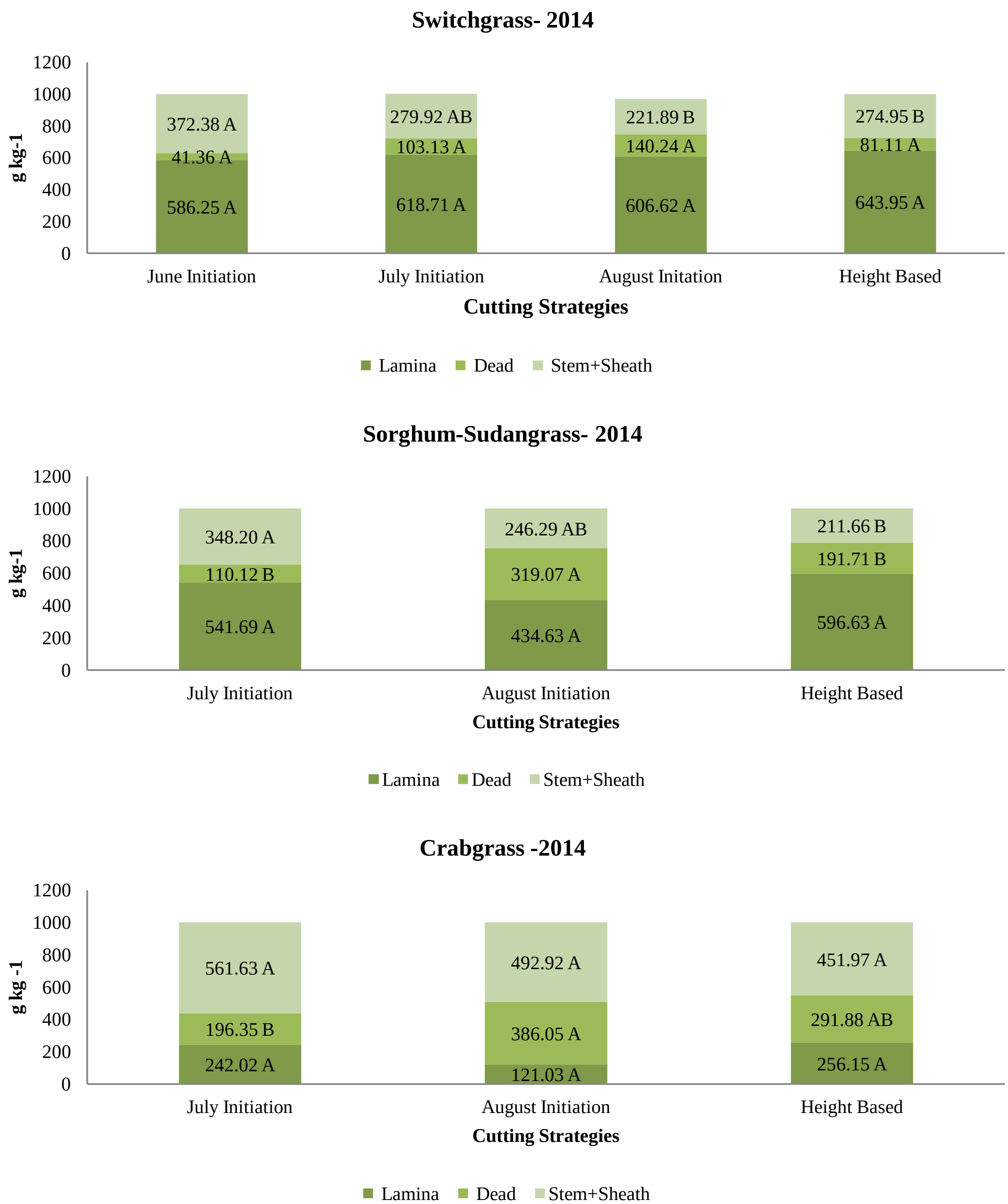


Figure 1.19. Relationship between neutral detergent fiber digestibility (NDFD) and herbage mass (HM) for monthly initiations (June, July, and August) and height based cutting of bermudagrass and crabgrass across the 2015 growing season at Plateau AgResearch and Education Center, Crossville, TN.



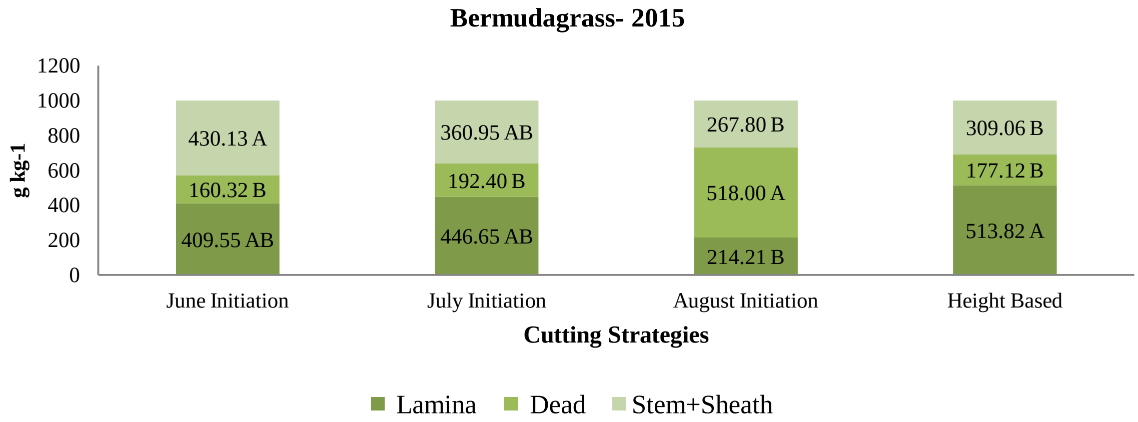
Means without a common letter differ (*P* < 0.05).

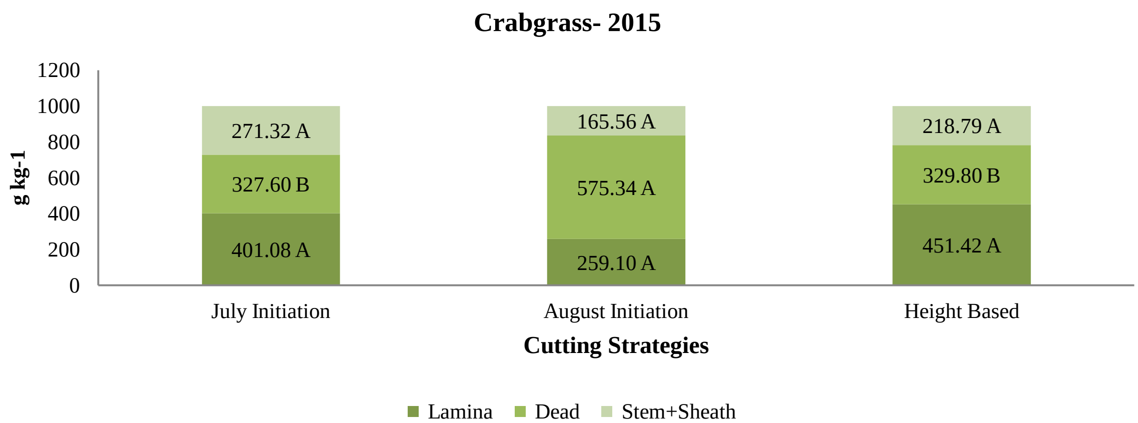
Figure 1.20. Morphological composition (lamina, stem+sheath, and dead material) of switchgrass, sorghum-sudangrass, and bermudagrass for the 2013 growing season at Plateau AgResearch and Education Center, Crossville, TN. Values are comparable by component, among management strategies



Means without a common letter differ (*P* < 0.05).

Figure 1.21. Morphological composition (lamina, stem+sheath, and dead material) of switchgrass, sorhum-sudangrass, and crabgrass for the 2014 growing season at Plateau AgResearch and Education Center, Crossville, TN. Values are comparable by component, among management strategies.





Means without a common letter differ (*P* < 0.05).

Figure 1.22. Morphological composition (lamina, stem+sheath, and dead material) of bermudagrass and crabgrass for the 2015 growing season at Plateau AgResearch and Education Center, Crossville, TN. Values are comparable by component, among management strategies.

CHAPTER 2:

Water-Use Efficiency of Annual and Perennial Warm-Season Forage Grasses

ABSTRACT

Beef producers need drought tolerant options when selecting forage grasses. The objective of this experiment was to use water use efficiency (WUE) to evaluate the productive potential of grass species during limited rainfall. This experiment consisted of a greenhouse study followed by a field study. Water use efficiency data was collected through a greenhouse experiment held at The University of Tennessee, Knoxville. Species tested included crabgrass (*Digitaria sanguinalis* cv. 'Red River'), switchgrass (*Panicum virgatum* (L.) cv. Alamo), big bluestem (*Andropogon gerardii* cv. 'OZ-70'), indiangrass (*Sorghastum nutans* cv. 'Rumsey'), eastern gamagrass (*Tripsacum dactyloides* cv. 'Pete'), and bermudagrass (*Cynodon dactylon* cv. 'Vaughn's #1'). The field experiment took place at the Highland Rim AgResearch and Education Center (HRREC) in Springfield, Tennessee and the Ames Plantation (APREC) AgResearch and Education Center in Grand Junction, Tennessee during the growing seasons of 2014 and 2015. Results aided in forming hypotheses of species performance in the field. The field experiment took place at the Highland Rim AgResearch and Education Center (HRREC) in Springfield, Tennessee and the Ames Plantation (APREC) AgResearch and Education Center in Grand Junction, Tennessee during the growing seasons of 2014 and 2015. Results indicated that WUE of switchgrass and eastern gamagrass were greater than indiangrass and bigbluestem at APREC , but species did not differ at HRREC. In addition WUE differed with time of year at HRREC, but did not at APREC. Temperature and WUE were positively correlated at both locations suggesting that as temperature increases, WUE increases.

INTRODUCTION

The Southeastern United States has been subjected to multiple severe drought events across the past decade (U.S. Drought Monitor, 2014) and climatologists expect this trend to continue in the future (Konrad II and Fuhrmann, 2013). Drought conditions have significantly reduced availability of quality forage. In 2007, the Southeast experienced an intense drought forcing many beef producers to downsize or eliminate their herds in an attempt to cope with the lack of forage (USDA NASS, 2015). Increasing the use of warm-season grasses in cattle systems could help minimize the impacts of future droughts and assist in maintaining beef production, which is the United States' largest agricultural sector (USDA NASS, 2015), during such times.

There are many grass species that have the ability to compensate for forage loss under drought. Introduced annual species, such as sorghum-sudangrass hybrids [*Sorghum bicolor* (L.) ×*Sorghum sudanese* (P.) cv. 'Greengrazer'], pearl millet (*Pennisetum glaucum* cv. 'Tiffleaf'), and crabgrass, can maintain a high stocking density, and produce forage of equivalent nutritive value to many commonly used cool-season grasses in the Southeast, such as tall fescue ([*Schedonorus arundinaceus* (Schreb.) Dumort.]). Native warm-season perennial grasses, such as switchgrass, big bluestem, indiangrass, and eastern gamagrass may also be suitable candidates to establish for drought tolerance (Koshi et al., 1982; Anderson and Matches, 1986; Sanderson and Reed, 2000; Stroup et al., 2003; Temu et al., 2014). These species are fully adapted to the region's climate, have few pest and disease problems, and have deep root systems (Keyser et al. 2013). In addition to large root masses, these species produce high amounts of herbage mass (HM), which when managed for grazing or hay production can provide enough energy to support animal growth and development (Koshi et al., 1982; Griffen and Jung, 1983; Temu et al., 2014). They have yields greater than commonly used cool-season grasses (C_3) in the region and require fewer inputs for production.

Water use efficiency, a ratio of water input to dry matter (DM) output, has been successfully used as an indication of plant tolerance to drought (Koshi et al., 1982; Kramer, 1983; Ghannoum et al., 2002; Anyia and Herzog, 2004; Taylor et al., 2009; Hussain et al., 2011; Jongen et al., 2011). However these measurements of WUE are subject to a great deal of error in field studies due to variations in soil type, topography, and stand densities. Instantaneous measurements of WUE (iWUE) can be made based on gas exchange rates in real-time using photosynthesis and transpiration rates directly from the leaf, while creating a controlled micro-environment (LI-COR Inc., Lincoln, NE).

Previous WUE studies have used iWUE to make inferences about the drought tolerance of forage crops, but few have examined the species included in this experiment and most have been conducted in a greenhouse setting. Beale et al. (1999) measured iWUE of two perennial C_4 grasses [miscanthus (*Miscanthus* x *giganteus*) and big cordgrass (*Spartina cynosuroides*)] in a temperate climate, but had inconclusive results. A greenhouse experiment by Taylor et al. (2009) studied many ecophysiological traits of C_3 and C_4 grasses including iWUE, which confirmed that C_4 grasses have greater WUEs, photosynthetic rates, and nitrogen-use efficiencies than C_3 grasses. Anyia and Herzog (2003) conducted a greenhouse experiment that studied cowpea (*Vigna unguiculata* L. “Walp.”) under drought, which showed that there were significant differences in WUE among varieties of cowpea and that iWUE and WUE based on the ratio of herbage accumulation to water inputs are not necessarily correlated. Ghannoum et al. (2002)

conducted a greenhouse experiment using the ratio of water input to DM output to measure drought resistance of Australian C_4 grasses and found that drought enhanced WUE. Studies by Jongen et al. (2011), using gas exchange and mass-based values of WUE, and Hussain et al. (2011), using mass-based WUE values, observed drought responses of mixed grasslands and found that WUE was enhanced when evapotranspiration rates increased.

Drought conditions are becoming more prevalent in many states of this region and impact animal producers via forage availability decline. Therefore, the objective of this experiment was to use WUE to evaluate the productive potential of warm-season grass species during limited rainfall. In this experiment, we tested WUE responses to drought in both a greenhouse and a field study using mass-based WUE values and gas exchange values. It was hypothesized that WUE of native perennial species would be competitive with bermudagrass and that WUE of crabgrass would be similar to the WUE of perennials early in the season. However, it was expected that differences in WUE would appear later in the season. Results of these experiments could serve to better prepare producers for stochastic weather events, thereby reducing profit loss under drought conditions. These results could have an impact on animal industry across fifteen neighboring states where the predominate forage grass is usually tall fescue.

MATERIALS AND METHODS

Experiment 1

Site Description

This study took place in a University of Tennessee greenhouse in Knoxville, TN (36° N, 83° W, 270-m altitude), with a randomized complete block design and four replications. Eight warm-season and one cool-season grass species were evaluated from October 29, 2013 to February 19, 2014. Warm-season species included five perennials (switchgrass, big bluestem, indiangrass, eastern gamagrass, and bermudagrass) and three annuals (crabgrass, sorghum-sudangrass, and pearl millet). The cool-season grass studied was tall fescue.

Measurements

In preparation for the greenhouse experiment, seedlings of each species were grown in plug trays of potting soil and then transplanted on October 29, 2013 into 10 cm x 10 cm x 23 cm pots (1.6 L). Etowah silt loam (fine-loamy, siliceous, semiactive, thermic Typic Paleudults) a moderately fine, well-drained soil formed in alluvium or colluvium that is commonly underlain by limestone residuum (NRCS, 2014), was collected at the East Tennessee AgResearch and Education Center's (ETREC) Plant Science Unit (35° 54' N 83° 57' W), autoclaved, and sifted for use. Pots were filled with soil, each to a consistent weight of 4.80 kg with no supplementary nutrients applied. Upon transplanting, root material and aboveground growth were trimmed to 14 cm from the plant base to leaf tip and 14 cm from plant base to root tip across all species, and total mass recorded.

Immediately following transplanting, pots were watered until the soil was fully saturated and were left undisturbed over night to reach stable water holding capacity then weighed; weights served as a guide to determine appropriate saturation levels throughout the remainder of the experiment (Byrd and May, 2000). Four plants per species were randomly assigned to stressed (dry) and well-watered (wet) treatments. Stressed and well-watered treatments were dictated by pot-capacity, which was equivalent to the maximum amount of water the test pots (averaged over all experimental units) could hold at 24-hours post soil saturation (Byrd and May, 2000).

An additional set of plants (1 plant per species per treatment) was prepared in the same manner and observed separately under water stress to observe when a negative plant growth response occurred and when gas exchange measurements could no longer be taken from the leaves. These observations were used to determine the appropriate pot-capacity needed to induce drought stress and to determine photosynthetic cessation at the end of the experiment.

Both wet and dry treatments were maintained at 90% pot-capacity from 30 October to 22 November to monitor transplants and observe rate of moisture loss (kg day^{-1}). From 23 November to 30 November dry treatments were maintained at 60% pot-capacity and wet treatments were maintained at 90% pot-capacity. A random sample of one experimental unit per species per treatment was weighed daily to determine water requirements for maintaining prescribed pot-capacities and then the appropriate amount of water (g) was applied to reach the desired capacity. Weights from perennials were pooled together and annuals were pooled together to determine the appropriate amount to water needed for each group.

To simulate drought, a sub-lethal dry down was implemented from 1 December – 7 December to induce drought stress. During this period, dry treatments dropped from 60% to 40% pot-capacity and wet treatments from 90% to 70% pot-capacity (these values were chosen based on observations of the pot-capacity at which dry treatment plants were fully wilted). Following the sub-lethal dry down period, dry and wet regimes returned to 60% and 90%, respectively, from 8 December-16 December. A lethal dry down period was implemented beginning on 17 December, in which watering was terminated for the remainder of the experiment. Observations were taken every three days and the date of photosynthetic cessation recorded for each pot with the last observation taken on February 19, 2014. Date of photosynthetic cessation was determined based on the ratio of necrotic plant tissue to green plant tissue, which was determined based on the point at which the gas exchange data could no longer be collected from the leaves. Once the ratio reached 4:1 it was assumed that the plants were no longer photosynthetically-active. Following plant death, herbage and root dry matter were recorded.

Gas exchange measurements were taken on four dates during the greenhouse study with the LI-6400 XT Portable Photosynthesis System (LI-COR Inc., Lincoln, NE). On each sampling date, one gas exchange data point was taken per plant. The average of four replications per treatment was used to represent the iWUE of each species upon that sampling date. The average of the four sampling dates was used to represent the overall iWUE of each species throughout the experiment.

Throughout data collection, CO_2 concentration in the leaf chamber was kept constant at 400 µmol CO_2 mol air^{-1}. Within the chamber, leaf temperature and photosynthetically active radiation (PAR) were adjusted to match the ambient levels in the greenhouse. Temperature in the greenhouse was kept as warm as possible during the study, with controls set to heat when temperatures reached 18°C and to cool when temperatures reached 29°C. Average daily temperature in the greenhouse was 21°C. Leaf temperature ranged from 24.0°C to 33.0°C and PAR ranged from 190.0 to 260.0 µmol m^{-2} s^{-1}. Data points from the newest emerged, fully expanded, photosynthetically-active leaf of each plant were used to record photosynthesis rate, transpiration rate, and leaf area. All data points were collected between 10:00 and 15:00 hours. Using these data points, an iWUE value was calculated for each experimental unit. The dates of the data collections were as follows: November 22, 2013, during the acclimation period (post-transplant, pre-treatment); November 26, 2013 during the wet and dry regime implementation; December 3, 2013 during sub-lethal dry down; and December 16, 2013 following rewetting (post sub-lethal, pre-lethal).

After all watering was terminated, date of photosynthetic cessation was recorded to determine the length of survival in days post-watering (DPW). At the end of the experiment, above-ground and below-ground plant material was collected to determine total dry matter produced per kilogram of water applied for each plant (g DM kg^{-1} H_2O). The average of the four replications per treatment was used to represent the WUE of each species.

Experiment 2

Site Description

The second experiment was conducted at the Highland Rim AgResearch and Education Center (HRREC) in Springfield, TN (36° 28' N, 86° 49' W, 203-m elevation), and at the Ames Plantation AgResearch and Education Center (APREC) in Grand Junction, TN (35° 8' N, 89° 12' W, 174-m elevation) during the growing seasons of 2014 and 2015. Paddocks were arranged in a completely randomized design with three replications. At HRREC, paddocks consisted of four species: switchgrass, crabgrass, and a mixed pasture of big bluestem and indiangrass, totaling 9 paddocks. At APREC, paddocks consisted of six species: switchgrass, crabgrass, bermudagrass, eastern gamagrass, and a mixed pasture of big bluestem and indiangrass, totaling 15 paddocks.

At both locations, experimental units were 1.21 ha^2 and continuously grazed by weaned stocker heifers from 16 May- 6 August 2014 and 15 May-17 August 2015 at HRREC and 13 May- 6 August 2014 and from 8 May- 17 August 2015 at APREC. Stocking rate was adjusted as needed to keep forage at a manageable height and allow adequate animal intake (50 cm for switchgrass, eastern gamagrass, bigbluestem, and indiangrass; 20 cm for crabgrass and bermudagrass). Bermudagrass paddocks were established in 2013 at a seeding rate of 11.22 kg ha^{-1} at both APREC and HRREC, however following an abnormally cold winter, bermudagrass was replanted at HRREC on May 13, 2014. Native perennial paddocks were established for a previous experiment in the spring of 2008 and 2009. Switchgrass and the indiangrass-big bluestem blend were seeded with a no-till drill at the following rates: indiangrass 3.53 kg ha^{-1}; big bluestem 6.55 kg ha^{-1}; and switchgrass 6.72 kg ha^{-1}. Eastern gamagrass was planted with a corn planter at 13.44 kg ha^{-1}. Crabgrass was seeded at 0.56 kg ha^{-1} into the paddocks on 8 May at HRREC and on 20 April at APREC in 2014. In 2015 crabgrass was seeded on 8 May at HRREC and 24 April at APREC.

The most prominent soil type in paddocks at HRREC was Sango silt loam (coarse-silty, siliceous, semiactive, thermic Glossic Fragiudults), a moderately well-drained soil formed in residuum weathered from cherty limestone, pH = 6.6 (NRCS, 2014) The most prominent soil type in paddocks at APREC was Memphis silt loam (Fine-silty, mixed, active, thermic Typic Hapludalfs), a well-drained soil formed in loess deposits, pH = 6.6 (NRCS, 2014). Based on soil tests at HRREC, switchgrass and big bluestem-indiangrass paddocks were fertilized with 60-0-0 at 146 kg ha^{-1} on May 12, 2014 and April 28, 2015. Crabgrass paddocks were fertilized with 60-30-60 at 345 kg ha^{-1}on May 27, 2014 and June 6, 2015. At APREC all the paddocks were fertilized with 60-0-0 at 67 kg ha^{-1} on 14 April 2014 and 2015.

Measurements

For the field study, WUE was recorded at each location approximately every 28-days. Measurements of WUE were collected on four occasions per year at HRREC (28 May, 25-26 June, 23-24 July, and 29-30 August, 2014 and 2-3 June, 29-30 June, 27-29 July, and 22-23 August, 2015) and at APREC (4-6 June, 8-10 July, 4-6 August, and 5-7 September, 2014 and 25-27 May, 23-25 June, 22-23 July, and 13-16 August, 2015).

Three samples were taken from each of three randomly placed grass cages per paddock. Cages protected leaves from defoliation by cattle and were randomly moved to new locations within the paddock two weeks before each sampling date to ensure that the forage measured had two weeks to regrow after grazing. Moving the cages also prevented sampling from the same plants twice.

In April 2015, Watermark 200SS soil moisture sensors (The Irrometer Company, INC. Riverside, CA) were placed at both HRREC and APREC in each paddock to take observations of soil tension throughout the experiment. Within each paddock, soil sensors were placed at two soil depths, 20 cm and 40 cm. Readings of soil water tension (ranging from 0-239 kPa, with zero being fully saturated) were collected from each sensor concurrent with iWUE sampling. Prior to installation, all sensors were calibrated to read 0 kPa at 100% saturation.

Gas exchange measurements were taken with the LI-6400 XT Portable Photosynthesis System (LI-COR Inc., Lincoln, NE). Leaf readings were taken from the most recently emerged, fully expanded, photosynthetically active leaf on the plant between 10:00 and 15:00 hours. Carbon dioxide concentration (400 μmol CO_2 mol air^{-1}) and light intensity (1500 μmol m^{-2} s^{-1}) were kept constant within the leaf chamber throughout the entire experiment. Appropriate PAR levels were established using data from light curves mapped in the greenhouse for each native species, with 1500 μmol m^{-2} s^{-1} being the average light compensation point. Leaf temperature in the chamber was set based on the ambient temperatures at the start of each sampling day and kept constant until the end of daily sampling. Over the whole study, leaf temperature ranged between 18.5°C and 39.1°C. Leaf area was recorded for each data point.

Gas exchange measurements were used to calculate iWUE. Measurements were taken in random order within replications and replication order was also randomized on each sampling date to account for diurnal fluxes throughout the paddocks. Additional observations of diurnal fluxes related to time of day, ambient light intensity, and ambient temperature were taken to correlate with WUE observations.

Statistical Analysis

Differences among least squares means of each species for both experiments were evaluated using the PROC MIXED procedures of SAS (SAS for Windows V 9.4, SAS Institute, Cary, NC). For the greenhouse experiment iWUE, WUE, and DPW were dependent variables with species, treatment, and lifecycle as fixed effects. Rep was a random effect and species*treatment interactions were tested. For the field experiment, locations were evaluated separately with iWUE as the dependent variable and species, cycle, and rep as fixed effects. Year was a random effect and species*cycle, cycle*year, year*species, and species*cycle*year interactions were tested. All data sets were checked for normality. Pearson Correlation Coefficients (PROC CORR) were used in SAS (SAS for Windows V 9.4, SAS Institute, Cary, NC) to test existent relationships between iWUE, temperature, humidity, and PAR in both the greenhouse and field experiments. The PROC GLM and PROC MIXED procedures were used to run analysis of covariance in SAS (SAS for Windows V 9.4, SAS Institute, Cary, NC) for mass as a covariate to iWUE with lifecycle as a random effect in the greenhouse. Soil moisture was tested as a covariate to iWUE with rep as a random effect in the field. All results were evaluated for significance at $P < 0.05$.

RESULTS

Experiment 1

Water Use Efficiency

Species iWUE differed, but treatment level did not have an impact on iWUE (Table 2.1). The three annual species were not different from switchgrass or eastern gamagrass. Crabgrass was not different from any of the native grasses. Bermudagrass and tall fescue were not different from indiangrass or big bluestem.

Both species and treatment level influenced WUE (Table 2.2). Results of the dry treatment indicate that bermudagrass differed from tall fescue, crabgrass, big bluestem, and eastern gamagrass, but did not differ from switchgrass, sorghum-sudangrass, pearl millet, or indiangrass. Results of the wet treatment indicate that sorghum-sudangrass differed from all species except pearl millet. Pearl millet did not differ from bermudagrass. Bermudagrass did not differ from crabgrass. The remaining species did not differ from one another.

Survival Length

Species had a significant impact on survival length but treatment level did not (Table 2.3). The average survival length for all species ranged from 12 to 57 DPW. Eastern gamagrass, big bluestem, and indiangrass survived the longer than the remaining species, while switchgrass survived longer than tall fescue, pearl millet, sorghum-sudangrass, bermudagrass, and crabgrass.

Correlations

Instantaneous water use efficiency, treatment, total mass, and length of survival were tested for Pearson correlations (Table 2.4). Results indicated that total mass was positively correlated to iWUE and negatively correlated to length of survival. Mass was then used as a covariate to iWUE (Table 2.5), but even though the r-square (0.6656) indicated a moderately strong relationship, it was not significant for any species tested.

Experiment 2

Weather

Temperatures recorded at both HRREC and APREC were near average in 2014 and 2015. In 2014, temperature from May through September at HRREC was 0.5°C higher than average (22.9°C) and in 2015, was 0.9°C higher than average. In 2014, temperature from May through

September at APREC was 0.2°C lower than average (23.9°C) and in 2015, was 0.6°C higher than average. From May through September in 2014, precipitation at HRREC was 23% lower than average (525 mm) and precipitation at APREC was 46% higher than average (561 mm). In 2015 from May through September, precipitation at HRREC was 13% lower than average and at APREC was 8% higher than average (Figure 2.1).

Water Use Efficiency

At HRREC iWUE by species did not differ, but at APREC, iWUE was different by species (Table 2.6). At APREC, eastern gamagrass, and switchgrass has greater iWUEs than big bluestem and indiangrass, but big bluestem and indiangrass did not differ from bermudagrass or crabgrass. At HRREC iWUE differed by sampling cycle, but did not at APREC (Table 2.7). At HRREC, cycle 4 yielded greater iWUEs than cycle 1 and 3. Cycle 2 did not differ from the other cycles.

Soil Moisture

Average soil tension at both locations and both depths across the 2015 growing season exceeded field capacity (~30 kPa). Although soil moisture ranged from fully saturated to near the permanent wilting point (~200 kPa) plants did not exhibit drought responses (Enciso et al., 2007) (Table 2.8).

Analysis of covariance did not indicate a consistent relationship between soil moisture and iWUE among species during 2015 (Table 2.9). At HRREC, the relationship was weak between soil moisture and iWUE at both 20 cm and 40 cm soil depths ($r^2 < 0.3$). At APREC, the relationship between soil moisture and iWUE was moderate ($r^2 = 0.3$ to 0.7) at both soil depths. With species pooled together at each location the interaction between species and soil moisture was not significant at either location or either soil depth. However, when species were analyzed separately with soil moisture, interactions were detected at APREC. There were significant interactions between bermudagrass and soil moisture at 20 cm and significant interactions between switchgrass and soil moisture at both 20 cm and 40 cm.

Correlations

For each location, iWUE, temperature, humidity, and PAR were tested for Pearson correlations. Results from HRREC indicated that temperature was positively correlated to iWUE and PAR (Table 2.10). No other variables were correlated. Results from APREC indicated that that temperature was positively correlated to iWUE and PAR, but negatively correlated to humidity (Table 2.11). No other variables were correlated.

DISCUSSION

Experiment 1

The plants tested in the greenhouse experiment were seedlings as opposed to the fully mature plants tested in the field experiment. All plants were the same age, however, the annual plants grew to sexual maturity and acquired mass quicker than the perennial plants. This was expected to occur due to the physiological differences between annuals and perennials and the completion of their lifecycles (Stern et al., 2008). Therefore, we applied water regimes specifically to annuals and perennials separately. Initial statistical analysis revealed that lifecycle was not significant on iWUE, WUE, or survival length and therefore, was omitted from future statistical analysis.

While temperature and PAR in the greenhouse were both lower than conditions observed in the field, they were consistent for all species tested during the experiment allowing an accurate comparison among species. However, had temperature and PAR been greater, it is likely that iWUE would also have been greater. Higher ratios of photosynthetic rate to transpiration rate were observed in the field at higher temperature and PAR, which is justified by the species light compensation points. The light compensation point is the point at which the uptake of CO_2 by the plant balances with the release of CO_2, and at this point, photosynthetic CO_2 assimilation is maximized (Taiz and Zeiger, 2002). During the greenhouse experiment, PAR was never high enough for any of the tested species to reach their corresponding light compensation points. This was because light from the source to the leaf canopy in the greenhouse during late fall-early winter dissipated rapidly. Mitchell et al. (2015) documented reduced photosynthetic rates for switchgrass under cool temperatures and low light intensities in a controlled greenhouse environment, such as ours.

Species was a significant factor on all variables tested, while treatment (Dry vs. Wet) was only significant on WUE in g DM kg^{-1} H_2O (Table 2.2). These results suggest that the drought imposed in the greenhouse did not impact the carbon assimilation rates of the species tested or their lengths of survival after termination of watering. Anyia and Herzog (2004) conducted an imposed drought study under greenhouse conditions which had variable results for different varieties of cowpea, some of which showed increased iWUE and some of which showed no change in iWUE under severe drought stress. It is possible that the species we tested in the greenhouse truly do not differ in iWUE under drought stress, or it could be that the drought imposed was not severe enough to trigger a significant response. Imposed drought did impact how much mass was accumulated by the plants, with greater g DM kg^{-1} H_2O being obtained under drought conditions (Table 2.2). Similar responses were observed by Ghannoum et al. (2002) on Australian C_4 grasses in an imposed drought greenhouse study. Had the plants been grown in less root restrictive pots, they may have accumulated additional below ground DM during the experiment, further increasing the g DM kg^{-1} H_2O produced throughout the experiment.

Correlations between variables tested suggest that as accumulation of DM increases, plant iWUE increases as well (Table 2.4). In addition correlations suggest that as total DM accumulation increases, length of survival post-watering decreases. This corresponds with the accepted theory that leaf expansion is highly sensitive to drought (Sadeas and Milroy, 1996). It has been repeatedly observed that when plants are under water stress the leaves they produced will have decreased leaf areas than when water is adequately available (Sadeas and Milroy, 1996; Anyia and Herzog, 2004; Hussain et al., 2011; Feng et al., 2013). Producing leaves with smaller areas and less mass will reduce transpiration loss and thereby increase survival length during drought. Because the correlation was significant, mass was tested as a covariate to iWUE, but no relationship existed (Table 2.5).

For most variables tested, sorghum-sudangrass and pearl millet were significantly different from the other species tested, whereas crabgrass was similar to the native grasses. It was rare for the native species to be significantly different from one another. Bermudagrass displayed variable differences between the other species tested. Due to the commonalities between the native grasses and crabgrass, crabgrass was selected as the annual to be tested in the field experiment (Tables 2.1 and 2.2).

Experiment 2

Significant differences in iWUE were found between years at both locations. This was likely attributed to cycle sampling dates and precipitation differing between years. In both years, sampling cycles occurred on a staggered schedule. In 2014, sampling began on 28 May at HRREC, followed by sampling at APREC from 4-6 June. In 2015, sampling began at APREC from 25-27 May, followed by sampling at HRREC from 2-3 June. Sampling cycles were adjusted in 2015 to begin at APREC because crabgrass was ready for stocking at APREC, but was still establishing at HRREC. This resulted in variation of sampling cycle dates at both locations between years. We know that these plants reach peak productivity in mid-summer (Yaromi et al., 2013) and where sampling cycle occurred in relationship to that peak was not consistent between years, which would create variation in iWUE (Ribeiro et al., 2006). Also precipitation was greater from May to September at APREC in 2014 than 2015 and precipitation at HRREC was lower in 2014 than in 2015, which would have created additional variation between years (Johnson and Asay, 1993). However, because year was a random effect in the model, years were analyzed together by location.

The WUE values observed in this experiment were similar to those observed in other studies for warm-season grasses (Beale et al., 1999; Hovenden, 2003; Xu et al., 2006; Ribeiro et. al, 2006; Mantlana et al.,2009; Taylor et al., 2010; Erickson et al., 2012), which confirms that the grasses tested in this study perform similarly to C_4 grasses of other regions. At HRREC iWUE by species did not differ, but at APREC, iWUE was different by species (Table 2.6). At APREC, eastern gamagrass, and switchgrass has greater iWUEs than big bluestem and indiangrass, but big bluestem and indiangrass did not differ from bermudagrass or crabgrass. At HRREC iWUE differed by sampling cycle, but did not at APREC (Table 2.7) These differences in iWUE between native species were similar to those observed in Experiment 1 (Table 2.1). Indiangrass and bigbluestem have shorter growth habits and smaller leaf areas than switchgrass and eastern gamagrass, which could result in indiangrass and bigbluestem having lower photosynthetic rates and therefore, lower iWUEs.

At HRREC, cycle 4 yielded greater iWUEs than cycle 1 and 3. Cycle 2 did not differ from the other cycles. Cycle 4 took place late in the growing season and temperatures were greater during cycle 4 than in the other cycles. Temperature is directly related the photosynthetic rate and therefore impacts WUE (Long, 1983). For C_4 plants, peak photosynthesis occurs near 40°C (Yamori et al., 2013), which leads us to believe that photosynthesis could have been inhibited early in the growing season. Beale et al. (1999) observed similar patterns when testing C_4 perennial grasses in the field in a temperate environment.

Precipitation at HRREC was slightly below the average in both years, but drought conditions were not observed during the experiment. Precipitation at APREC was above average in both years (Figure 2.1). Average soil water tension was less than 100 kaP at both locations and both soil depths in 2015, confirming that moisture conditions were adequate for plant growth as deep as 40 cm across the 2015 growing season (Table 2.8). Gas exchange is impacted by plant available water when drought ensues, although leaf expansion is more sensitive to drought and is visually noticeable (Sadras and Milroy, 1996). Had drought occurred in 2014 or 2015 there could have been additional differences among species and/or cycle WUE, such as was observed by Hussain et al. (2011) during 2003 and 2004 on managed grasslands in Germany and as was observed by Jongen et al. (2011) from 2004 to 2008 on a Mediterranean grassland in Portugal.

At both HRREC and APREC, temperature was positively correlated with iWUE, suggesting that iWUE would be enhanced by increases in temperature (Table 2.10 and 2.11). Temperature was also positively correlated to PAR, suggesting that temperatures are greater when light intensity is high. At APREC, humidity was negatively correlated to temperature which corresponds with findings of Asher et al. (2013) for corn (*Zea mays*).

The individual observations of iWUE from this study provided readings of what is physiologically occurring on one leaf of the plant at that moment, which can easily be influenced by small changes in the plant or environment, such as energy partitioning or soil moisture, that cannot be controlled within the leaf chamber of the infrared gas analyzer (Beale et al., 1999). Therefore, there is a possibility that the data captured were not a true representation of the changes in iWUE that occur across the growing season among species. Instating more frequent sampling cycles (7 or 14 day sampling cycles instead of 28) and keeping the dates of the sampling cycles consistent between years could have eliminated much of the variation we encountered.

CONCLUSIONS

Under imposed drought in the greenhouse, crabgrass iWUE was similar to the native grasses, which led to its selection for screening in the field study during 2014 and 2015. Data collected in the greenhouse confirmed that WUE in g DM kg^{-1} H_2O was enhanced by drought in all species tested. In addition, results suggested that plants which produce large amounts of dry matter will survive for shorter time periods during drought than plants with low amounts of dry matter production.

Of the species tested in the field, bermudagrass, crabgrass, eastern gamagrass, and switchgrass never differed from one another. Indiangrass and bigbluestem were lower than eastern gamagrass and switchgrass at APREC. In neither 2014 nor 2015 was drought present. Further study of these species must be conducted in future years to either confirm similar performance during all moisture conditions or to detect differences between species during drought which ensues over the growing season.

Results from the conducted experiment suggest that all the native grasses have greater WUEs than cool-season grasses which are commonly used in pastures of the region. Crabgrass performs similarly to the native grasses and could be used as an emergency annual crop to assist in meeting animal feeding requirements in place or supplementation of a struggling perennial crop.

APPENDIX B

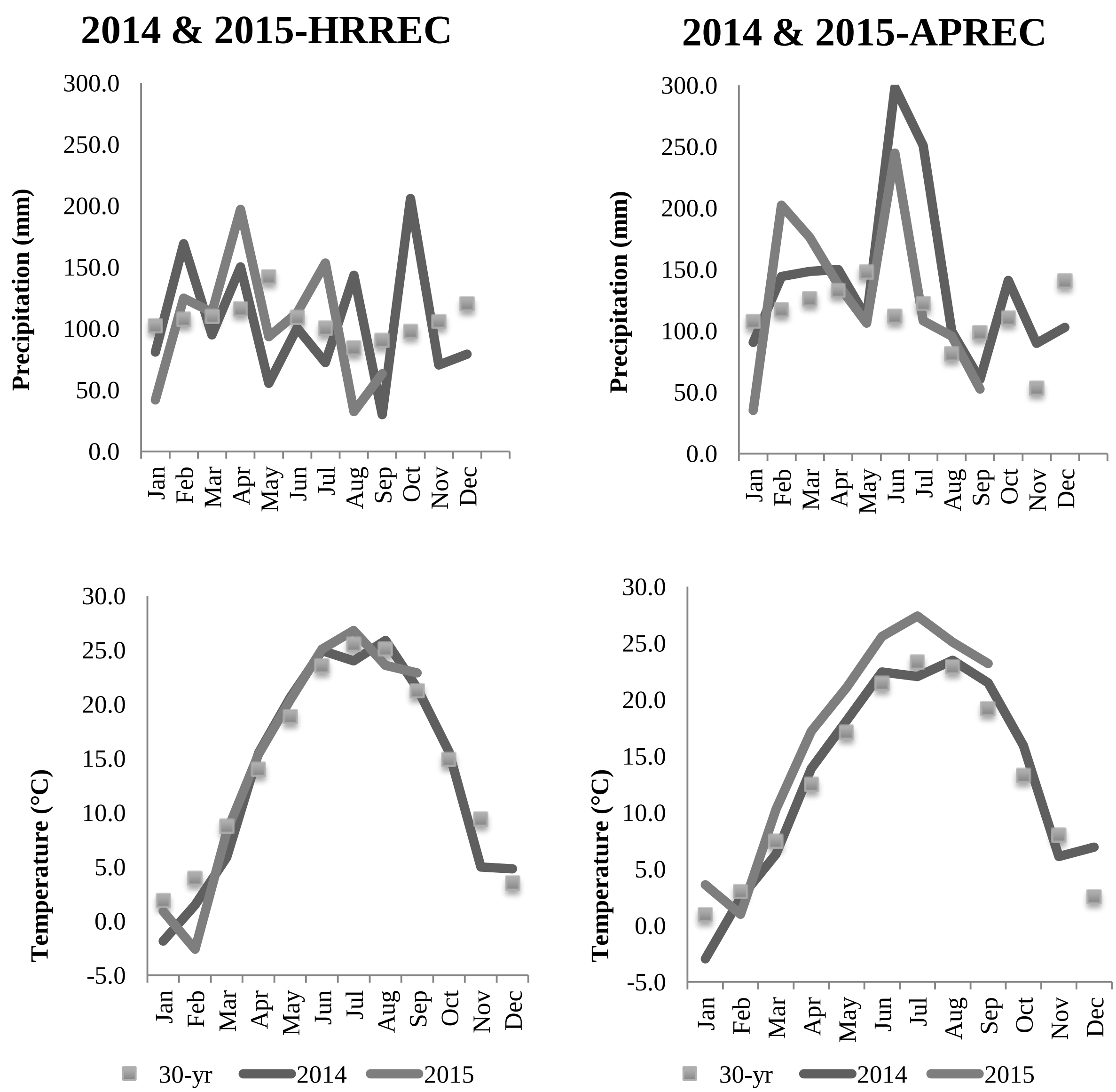


Figure 2.1. Weather recorded at Highland Rim AgResearch and Education Center, Springfield, TN and Ames Plantation AgResearch and Education Center, Grand Junction, TN during 2014 and 2015 with the 30-year average.

Table 2.1. Least squares means of iWUE by species tested in the greenhouse across the four sampling dates in µmol CO_2 mol H_2O^{-1} at The University of Tennessee, Knoxville, TN greenhouse in 2013.

Species	Mean	Min.	Max.	STDV
sorghum-sudangrass	47.21[a]	31.89	64.88	11.53
pearl millet	46.04[a]	24.98	54.16	9.09
crabgrass	39.80[ab]	26.64	48.99	6.66
switchgrass	35.19[ab]	21.01	52.08	8.21
eastern gamagrass	34.76[ab]	31.22	39.20	2.37
indiangrass	28.06[b]	21.04	36.03	4.91
big bluestem	27.48[b]	21.53	37.36	4.61
bermudagrass	20.28[b]	6.55	36.28	9.87
tall fescue	15.20[b]	10.00	24.56	4.60

Means within a column without a common superscript letter differ (*P* < 0.05).

Table 2.2. Least squares means WUE of each species tested across the four sampling dates in g DM kg^{-1} H_2O at The University of Tennessee, Knoxville, TN greenhouse in 2013.

Treatment	Species	Mean	Min.	Max.	STDV
Dry					
	bermudagrass	25.91[a]	18.18	32.73	5.20
	switchgrass	22.72[ab]	16.36	32.73	6.10
	sorghum-sudangrass	21.48[ab]	17.48	26.70	4.10
	pearl millet	18.43[abc]	16.02	20.87	1.92
	indiangrass	16.82[abc]	12.73	23.64	4.14
	tall fescue	16.82[bc]	9.09	21.82	4.87
	crabgrass	14.93[bc]	13.11	16.02	1.11
	big bluestem	12.27[bc]	9.09	14.54	2.36
	eastern gamagrass	11.82[bc]	7.27	16.36	3.28
Wet					
	sorghum-sudangrass	23.92[a]	11.35	36.76	12.44
	pearl millet	16.96[ab]	15.14	20.81	2.26
	bermudagrass	14.93[bc]	8.87	16.94	1.11
	crabgrass	8.24[cd]	7.30	10.00	1.11
	switchgrass	7.86[cd]	4.84	12.10	2.87
	tall fescue	7.66[cd]	5.65	8.87	1.21
	eastern gamagrass	7.46[cd]	3.23	16.94	5.51
	indiangrass	6.65[cd]	3.23	10.48	2.82
	big bluestem	4.44[d]	3.23	6.45	1.34

Means within a column for each treatment without a common superscript letter differ ($P < 0.05$). Treatment was significant ($P < 0.01$).

Table 2.3. Least squares means by length of survival by species tested in the greenhouse in days post watering (DPW) at The University of Tennessee, Knoxville, TN greenhouse in 2013.

Species	Mean	Min.	Max.	STDV
eastern gamagrass	45.75[a]	34	57	7.48
big bluestem	40.75[a]	29	47	5.78
indiangrass	39.63[a]	29	50	7.65
switchgrass	29.75[b]	22	39	6.30
tall fescue	21.50[c]	20	22	0.87
pearl millet	19.25[c]	18	22	1.48
sorghum-sudangrass	18.13[c]	12	22	2.93
bermudagrass	17.25[c]	15	18	1.30
crabgrass	15.75[c]	15	18	1.30

Means within a column without a common superscript letter differ (*P* < 0.05).

Table 2.4. Pearson Correlations between Treatment, iWUE, DPW, and Mass in the greenhouse for all species tested at The University of Tennessee, Knoxville, TN greenhouse in 2013.

Variables	**Coefficients**
Treatment to iWUE	-0.05
Treatment to DPW	0.10
Treatment to Mass	0.17
iWUE to DPW	-0.15
iWUE to Mass	0.61*
DPW to Mass	-0.56*

* **Significant at P < 0.05**

Table 2.5. Analysis of covariance between iWUE and Mass for all species tested at The University of Tennessee, Knoxville, TN greenhouse in 2013.

----------Species*Mass----------		
Species	*P*-Value	r^2
Bermudagrass	0.7369	
Big Bluestem	0.3613	
Crabgrass	0.1952	
Eastern Gamagrass	0.8671	
Indiangrass	0.3568	
Pearl Millet	0.2472	
Sorghum-Sudangrass	0.5779	
Switchgrass	0.0767	
Tall Fescue	0.7976	
All Species	0.4881	0.6656

Table 2.6. Least squares means of iWUE by species tested in the field at Highland Rim AgResearch and Education Center, Springfield, TN and Ames Plantation AgResearch and Education Center, Grand Junction, TN across the four sampling cycles in μmol CO_2 mol H_2O^{-1}.

Location	------------------- Species -------------------------						STDV	*P*-value
	Bermudagrass	Big Bluestem	Crabgrass	Eastern Gamagrass	Indiangrass	Switchgrass		
HHREC	______	63.18[a]	73.85[a]	______	65.70[a]	73.30[a]	18.26	0.1391
APREC	50.67[ab]	46.01[b]	56.39[ab]	60.59[a]	47.30[b]	63.99[a]	18.33	0.0004

Means within a row without a common superscript letter differ (*P* < 0.05).

Table 2.7. Least squares means of iWUE by cycle tested in the field at Highland Rim AgResearch and Education Center, Springfield, TN and Ames Plantation AgResearch and Education Center, Grand Junction, TN in μmol CO_2 mol H_2O^{-1}.

Location	------------------- Cycle -------------------------				*P*-value
	1	2	3	4	
HHREC	53.92[c]	74.78[ab]	61.72[bc]	85.07[a]	<0.0001
APREC	49.13[a]	56.49[a]	53.68[a]	57.40[a]	0.1110

Means within a row without a common superscript letter differ (*P* < 0.05).

Table 2.8. Soil tension observed at Highland Rim AgResearch and Education Center, Springfield, TN and Ames Plantation AgResearch and Education Center, Grand Junction, TN in 2015.

Location	Depth	Mean	Min	Max
HHREC	20 cm	69.64 kPa	0 kPa	199 kPa
HRREC	40 cm	92.94 kPa	1 kPa	199 kPa
APREC	20 cm	34.33 kPa	0 kPa	163 kPa
APREC	40 cm	53.13 kPa	1 kPa	199 kPa

Table 2.9. Analysis of covariance between soil moisture and iWUE by species at Highland Rim AgResearch and Education Center, Springfield, TN and Ames Plantation AgResearch and Education Center, Grand Junction, TN in 2015.

		------------------- Species x Soil Moisture *P*-values -------------------------						
Location	Depth	Crabgrass	Switchgrass	Bermudagrass	Eastern Gamagrass	Big Bluestem-Indiangrass	All Species	r^2
HHREC	20 cm	0.0604	0.1738	________	_______	0.1272	0.0617	0.1898
HRREC	40 cm	0.3246	0.4403	________	_______	0.6648	0.6180	0.0507
APREC	20 cm	0.8941	0.0285	0.0545	0.8941	0.4424	0.1010	0.3409
APREC	40 cm	0.5774	0.0144	0.0718	0.8301	0.3616	0.0918	0.3511

Table 2.10. Pearson Correlations between iWUE, Temperature, Humidity, and PAR in the field at Highland Rim AgResearch and Education Center, Springfield, TN for all species.

Variables	**Coefficients**
iWUE to Temperature	0.44*
iWUE to Humidity	-0.15
iWUE to PAR	0.12
Humidity to Temperature	-0.20
Humidity to PAR	0.13
Temperature to PAR	0.64*

***Significant at *P* < 0.05**

Table 2.11. Pearson Correlations between iWUE, Temperature, Humidity, and PAR in the field at Ames Plantation AgResearch and Education Center, Grand Junction, TN for all species.

Variables	**Coefficients**
iWUE to Temperature	0.68*
iWUE to Humidity	-0.46*
iWUE to PAR	0.21
Humidity to Temperature	-0.48*
Humidity to PAR	0.16
Temperature to PAR	0.48*

***Significant at *P* < 0.05**

CONCLUSION

Warm-season grasses are good alternatives to commonly used cool-season grasses to extend the grazing season, provide available forage during summer drought in the southeast. In order to provide animals with high-quality forage, practical methods are needed to estimate nutritive value to optimize harvest timing., which was the objective of the first experiment. After studying the effects of cutting strategies on CP and NDFD, both height based multiple cuttings or early season single cuts are recommended for all species in experiment 1. Nutritive value can significantly decline in August, therefore if using a single cutting harvest technique, harvest should be completed by early July. Crude protein of switchgrass, sorghum-sudangrass, and bermudagrass can be predicted by HM. In addition, CP was highly correlated to the morphological composition of the strata. Neutral detergent fiber digestibility was not reliably predicted by HM in any species examined. Additionally, results of this study did not indicate significant relationships between CP or NDFD and HM in the cases of crabgrass. Further research should be conducted on bermudagrass and crabgrass investigating these relationships.

Drought conditions are becoming more prevalent in many states of this region and impact animal producers via forage availability decline. Therefore, the objective of the second experiment was to use WUE to evaluate the productive potential of warm-season grass species during limited rainfall.

Under imposed drought in the greenhouse crabgrass iWUE was similar to the native grasses, which led to its selection for screening in the field study during 2014 and 2015. Data collected in the greenhouse confirmed that WUE in g DM kg^{-1} H_2O was enhanced by drought in all species tested. In addition, results suggested that plants which produce large amounts of dry matter will survive for shorter time periods during drought than plants with low amounts of dry matter production.

Of the species tested in the field, eastern gamagrass and switchgrass had greater iWUEs than big bluestem and indiangrass at APREC. At HRREC, sampling cycle 4 iWUE was greater than cycle 1. However, in neither 2014 nor 2015 was drought present. Further studies should be conducted in future years to either confirm similar performance during all moisture conditions or to detect differences between species during drought which ensues over the growing season. All the native grasses tested have greater WUEs than cool-season grasses which are commonly used in pastures of the region. Crabgrass performs similarly to the native grasses and could be used as an emergency annual crop to assist in meeting animal feeding requirements in place or supplementation of a struggling perennial crop.

Results of these experiments can be used to prepare producers for stochastic weather events, thereby reducing profit loss under drought conditions in the southeastern United States.

REFERENCES

Anderson, Bruce, and A. G. Matches. "Forage Yield, Quality, and Persistence of Switchgrass and Caucasian Bluestem." *Agronomy Journal* 75.Jan.-Feb. (1983): 119-24. Print.

Anderson, B. A. and P. Guyer. 1986. Summer Annual Forage Grasses. University of Nebraska Lincoln, NebGuide G74-171-A.

Asher, J. Ben, A. Garcia Y Garcia, I. Flitcroft, and G. Hoogenboom. "Effect of Atmospheric Water Vapor on Photosynthesis, Transpiration, and Canopy Conductance: A Case Study in Corn." *Plant Soil Environment* 59.12 (2013): 549-55. Web.

Ball, D., E. Ballard, M. Kennedy, G. Lacefield, and D. Undersander. *Extending Grazing and Reducing Stored Feed Needs*. Bryan, TX: Grazing Land Conservation Initiative, 2008. Print.

Ball, D. M., C. S. Hoveland, and G. D. Lacefield. Southern Forages: Modern Concepts for Forage Crop Management. Norcross, GA: Potash & Phosphate Institute and the Foundation for Agronomic Research, 2007. Print.

Bailey, R.W. 1973. Structural carbohydrates. P. 157-212. *In* G.W. Butler and R.W. Bailey (ed.) Chemistry and biochemistry of herbage. I. Academic Press, New York, NY.

Barker, D.J., F.P. Ferraro, R.L.G. Nave, R.M. Sulc, F. Lopes, and K.A. Albrecht. “Analysis of Herbage Mass and Herbage Accumulation Rate Using Gompertz Equations.” Agron. J. 102 (2010): 849‑857. Print.

Bates, G. *High-quality Hay Production*. Knoxville: UT Extension, 2007. Print.

Beale, Clive V., James I. L. Morison, and Steve P. Long. "Water Use Efficiency of C_4 Perennial Grasses in a Temperate Climate." *Agriculture and Forest Meteorology* 96 (1999): 103-15.Web.

Beck, P. A., S. Hutchinson, C. B. Stewart, S. D. Shockey, and S. A. Gunter. "Effect of Crabgrass (*Digitaria ciliaris*) Hay Harvest Interval on Forage Quality and Performance of Growing Calves Fed Mixed Diets." *Journal of Animal Science* 85 (2007): 527-35. Web. 6 June 2015.

Belesky, D. P., Fedders, and M. James. "Warm-Season Grass Productivity and Growth Rate as Influenced by Canopy Management." Agron. J. 1995. 87:42–48. Print.

Belesky,D.P., H. D. Perry, W. R. Windham, E. L. Mathias, and J. M. Fedders. "Productivity and Quality of Bermudagrass in a Cool Temperate Environment." Agron. J. 1991. 83:810-813. Print.

Bosworth, S. C., C. S. Hoveland, G.A. Buchanan, and W.B. Anthony. *Forage Quality of Selected Warm-Season Weed Species*. Agron. J. 1980. 72:1050-54. Print.

Burns, J. C., and D. S. Fisher. "'Coastal' and 'Tifton 44' Bermudagrass Availability on Animal and Pasture Productivity." *Agronomy Journal*100.5 (2008): 1280-288. Web. 12 June 2015.

Burns, J.C., K.R. Pond, D.S. Fisher, and J.M. Luginbuhl. 1997. Changes in forage quality, ingestive mastication, and digesta kinetics resulting from switchgrass maturity. J. Anim. Sci. 75:1368–1379.

Burns, J. C., R. D. Mochrie, and D. H. Timothy. "Steer Performance from Two Perennial *Pennisetum* Species, Switchgrass, and a Fescue- 'Coastal' Bermudagrass System." *Agronomy Journal* 76.Sept.-Oct. (1984): 795-800. Web. 6 June 2015.

Buxton, D.R. and S.L. Fales. 1994. "Plant Environment and Quality*" Forage quality, evaluation, and utilization*. Wisconsin, Madison: ASA, CSSA, and SSSA. 155-99. Print.

Byrd, G. T., and P. A. May. "Physiological Comparisons of Switchgrass Cultivars Differing in Transpiration Efficiency." *Crop Science* 40.5 (2000): 1271-277. Print.

Difante, G.S.; Nascimento Júnior, D.; Silva, S.C.; Euclides, V.P.B.; Zanine, A.M.; Adese, B. Tillering dynamics of marandu palisadegrass submitted to two cutting heights and three cutting intervals. *Rev. Bras. Zootec.* 2008, *37*, 189–196.

Fick, G.W., P.W. Wilkens, and J.H. Cherney. 1994. "Modeling forage quality changes in the growing crop.*" Forage quality, evaluation, and utilization*. Wisconsin, Madison: ASA, CSSA, and SSSA. 757-95. Print.

FOSS NIRS. Vers. 5000 Feed and Forage Analyzer. Denmark. FOSS.

George, J. R., and Doug Obermann. "Spring Defoliation to Improve Summer Supply and Quality of Switchgrass." *Agronomy Journal* 81.Jan-Feb (1989): 47-52. Web.

Ghannoum, Oula, Susanne Von Caemmerer, and Jann P. Conroy. 2002. *The effect of drought on plant water use efficiency of nine NAD-ME and nine NADP-ME Australian C_4 grasses.* Functional Plant Biology. 29: 1337-48. Print.

Griffen, J. L. and G. A. Jung. 1983. *Leaf and Stem Forage Quality of Big Bluestem and Switchgrass.* Agron. J. 75: 723-26. Print.

Griffen, J. L., and V. H. Watson. "Production and Quality of Four Bermudagrasses as Influenced by Rainfall Patterns." *Agronomy Journal* 74.Nov.-Dec. (1982): 1044-047. Web. 6 June 2015.

Henderson, M. S., and D. L. Robinson. "Environmental Influences on Yield and In Vitro True Digestibility of Warm-Season Perennial Grasses and the Relationships to Fiber Components." *Agronomy Journal* 74.Nov.-Dec. (1982): n. pag. Web. 6 June 2015.

Hirata, M., E. Kunieda, and M. Tobisa. "Short-term Ingestive Behaviour of Cattle Grazing Tropical Stoloniferous Grasses with Contrasting Growth Forms." *Journal of Agricultural Science* 148 (2010): 615-24. Web. 6 June 2015.

"History of the NIRSC." *NIRS Forage & Feed Testing Consortium*. NIRS Forage & Feed Testing Consortium, 2015. Web. 26 Feb. 2015.

Hovenden, Mark. "Growth and Photosynthetic Responses to Elevated [CO_2] in Grasses from Tasmanian Pasture." *Papers and Proceedings of the Royal Society of Tasmania* 137 (2003): 81-86. Web.

Hussain, M. Z., T. Grunwald, J. D. Tenhunen, Y. L. Li, H. Mirzae, C. Bernhofer, D. Otieno, N. Q. Dinh, M. Schmidt, M. Wartinger, and K. Owen. "Summer Drought Influence on CO2 and Water Fluxes of Extensively Managed Grassland in Germany." *Agriculture, Ecosystems and Environment* 141 (2011): 67-76. Print.

Jarl, F., T. Helleday. 1951. Studies of the changes in the chemical composition, digestibility and nutritive value of herbage at different growth stages (in Swedish) K." *Lantbr. Tidskr* 90: 315-335.

Jurgens, Marshall H., Kristjan Bregendahl, Josei Coverdale, and Stephanie Hansen. *Animal Feeding & Nutrition*. Kendall Hunt, 2012. Print.

Johnson, Douglas A., and Kay A. Asay. "Selection for Improved Drought Response in Cool-Season Grasses." *Society for Range Management* 16.3 (1993): 194-202. Web.

Jongen, Marjan, Joao Santos Pereira, Luis Miguel Aires, and Casimiro Adriao Pio. "The Effects of Drought and Timing of Precipitation on the Inter-annual Variation in Ecosystematmosphere Exchange in a Mediterranean Grassland." *Agricultural and Forest Meteorology* 151 (2011): 595-606. Print.

Kalu, B. A., G. A. Fick, and P. J. Van Soest. 1990. Agronomic factors in evaluating forage crops. II. Predicting fiber components (NDF, ADF, ADL) from crop leafiness. J. Agron. Crop Sci. 164:26-33.

Karn, J.F., J.D. Berdahl, and A.B. Frank. 2006. Nutritive quality of four perennial grasses as affected by species, cultivar, maturity, and plant tissue. Agron. J. 98:1400‑1409.

Keyser, P., C. Harper, G. Bates, J. Waller, and E. Doxon. *Native Warm-Season Grasses for Mid-South Forage Production*. Knoxville: UT Extension, 2013. Print.

Keyser, P. D., G. E. Bates, J. C. Waller, C. A. Harper, and E. D. Doxon. *Producing Hay From Native Warm-Season Grasses in the Mid-South*. Knoxville: UT Extension, 2011. Print.

Konrad II, Charles E. "Climate of the Southeast USA: Past, Present, and Future." *Climate of the Southeast United States*. Ed. Christopher M. Fuhrmann. N.p.: NCA Regional Input Reports, 2013. 8-42. Print.

Koshi, P.T., J. Stubbendieck, H. V. Eck, & W. G. McCully. (1982). Switchgrasses: Forage Yield, Forage Quality and Water-Use Efficiency. *Journal of Range Management*, *35*(5), 623–627.

Kramer, P. J. "Water Use Efficiency." *Water Relations of Plants*. New York, NY: Academic, 1983. 405-12. Print.

LI-6400 XT. Portable Photosynthesis Meter. Lincoln, Nebraska. LI-COR Biosciences Inc.

Long, S. P. "C_4 Photosynthesis at Low Temperature." *Plant, Cell and Environment* 6 (1983): 345-63. Web.

Mantlana, K. B., E. M. Veenendaal, A. Arneth, V. Grispen, C. M. Bonyongo, and I. G. Heitkonig. "Biomass and Leaf-level Gas Exchange Characteristics of Three African Savanna C_4 Grasses under Optimum Growth Conditions." *African Journal of Ecology* 47 (2009): 482-89. Web.

Mertens, D. R. "Forage Management." *Measurements of Forage Quality*. Proc. Of Tri-State Dairy Nutrition Conference, Indiana, Fort Wayne. Madison: Mertens Innovation and Research, LLC., 2011. Web.

Mertens, David R. "Measuring DM and NDF Digestibility and Defining Their Importance." 2002 NIRS Consortium Meeting. *USDA Agricultural Research Service*. Web. 26 Feb. 2015.

Moore, K.J., L.E. Moser, K.P. Vogel, S.S. Waller, B.E. Johnson, and J.F. Pederson. 1991. Describing and quantifying growth stages of perennial forage grasses. Agron. J. 83:1073–1077.

Murata, Yoshio and Junichiro Iyama. "Studies on the Photosynthesis of Forage Crops : II. Influence of air-temperature upon the photosynthesis of some forage and grain crops." *Japanese Journal of Crop Science.* 31.4 (1962): 315-322.

"NASS - National Agricultural Statistics Service." NASS - National Agricultural Statistics Service. USDA. Web. 30 Oct. 2014.

Nave, R. L.G., M. Sulc, and D. J. Barker. "Relationships of forage nutritive value to cool-season grass canopy characteristics." *Crop Science.* 53.1(2013): 341-348.

Nave, Renata L. G., R. Mark Sulc, David J. Barker, and Normand St-Pierre. "Changes in Forage Nutritive Value among Vertical Strata of a Cool-Season Grass Canopy."*Crop Science.* 54.6 (2014): 2837-2845

Nelson, C.J. and L.E. Moser. 1994. "Plant Factors Affecting Forage Quality.*" Forage quality, evaluation, and utilization*. Wisconsin, Madison: ASA, CSSA, and SSSA. 757-95. Print

Reich, Jonathan M. Brown Midrib Sudangrass Inbred 'cw R.1006-55' Jonathan M. Reich, assignee. Patent US20080098494 A1. 24 Apr. 2008. Print.

Reid, R. L. 1994. "Milestones in Forage Research (1969-1994).*" Forage quality, evaluation, and utilization*. Wisconsin, Madison: ASA, CSSA, and SSSA. 1-58. Print.

Reid, R .L., G. A. Gung, J. M. Cox-ganser, B. F. Rybeck, and E. C. Townsend. *Comparative utilization of warm- and cool-season forages by cattle, sheep and goats.* Journal of Animal Science. 1990. Vol.68 (9). 2986-94. Print.

Ribeiro, R. V., G. B. Lyra, A. V. Santiago, A. R. Pereira, E. C. Machado, and R. F. Oliveira. "Diurnal and Seasonal Patterns of Leaf Gas Exchange in Bahiagrass (*Paspalum Notatum* Flugge) Growing in a Subtropical Climate." *Grass and Forage Science* 61 (2006): 293-305. Web.

Richner, J.M., R.L. Kallenbach, C.A. Roberts. 2014. Dual use switchgrass: managing switchgrass for biomass production and summer forage. Agron. J. 106:1438-1444.

Sanderson, M. A., and R. L. Reed. "Switchgrass Growth and Development: Water, Nitrogen, and Plant Density Effects". *Journal of Range Management* 53.2 (2000): 221–227. Web.

SAS. Vers. 9.4. Cary, NC, USA: SAS Institute Inc., 2009.

Saxton, Arnold M. "SAS Error Using PROC MIXED in 9.4." Message to the author. 26 May 2015. E-mail.

Schroeder, J. W. *Forage Nutrients for Ruminants*. N.p.: North Dakota State University, 2013. Print.

Shenk, J. S. and M. O. Westerhaus. 1994. "The Application of Near Infrared Reflectance Spectroscopy (NIRS) to Forage Analysis.*" Forage quality, evaluation, and utilization*. Wisconsin, Madison: ASA, CSSA, and SSSA. 406-49. Print.

Stroup, J. A., M. A. Sanderson, J. P. Muir, M. J. McFarland, and R. L. Reed. "Comparison of Growth and Performance in Upland and Lowland Switchgrass Types to Water and Nitrogen Stress." *Bioresource Technology* 86.1 (2003): 65-72. Web.

Stern, Kingsley R., James E. Bidlack, and Shelley Jansky. *Introductory Plant Biology*. Eleventh ed. Boston: McGraw-Hill Higher Education, 2008. Print.

Stuth, Jerry, Abdi Jama, and Doug Tolleson. "Direct and Indirect Means of Predicting Forage Quality through near Infrared Reflectance Spectroscopy." *Field Crops Research* 84 (2003): 45-56. Print.

Taiz, Lincoln, and Eduardo Zeiger. "Photosynthesis: Carbon Reactions." *Plant Physiology*. Sunderland, MA: Sinauer Associates, 2002. 145-70. Print.

Taiz, Lincoln, and Eduardo Zeiger. "Photosynthesis: Physiological and Ecological Considerations." *Plant Physiology*. Sunderland, MA: Sinauer Associates, 2002. 171-192. Print.

Taylor, Samuel H., Stephen P. Hulme, Mark Rees, Brad S. Ripley, F. Ian Woodward, and Colin P. Osborne. "Ecophysiological Traits in C_3 and C_4 Grasses: A Phytogenetically Controlled Screening Experiment." *New Phytologist* 185.3 (2010): 780-91. Print.

Temu, Vitalis W., Brian J. Rude, and Brian S. Baldwin. "Nutritive Value Response of Native Warm-Season Forage Grasses to Harvest Intervals and Durations in Mixed Stands." *Plants* 3 (2014): 266-83. Web. 6 June 2015.

Teutsch, Chris D., John H. Fike, and W. Mac Tilson. "Yield, Digestibility, and Nutritive Value of Crabgrass as Impacted by Nitrogen Fertilization Rate and Source." *Agronomy Journal* 97.Nov.-Dec. (2005): 1640-646. Web. 12 June 2015.

Thomas Wiley Mill. Model 4. Swedesboro, NJ, USA. Thomas Scientific. *Using the LI-6400 XT Portable Photosynthesis System*. 10th ed. Lincoln: LI-COR, 2011. Print.

United States Department of Agriculture. Texas Cooperative Extension.*Irrigation Monitoring with Soil Water Sensors*. By Juan M. Enciso, Dana Porter, and Xavier Perles.: Texas A&M University, 2007. Print.

Vona, L.C.; Jung, G.A.; Reid, R.L.; Sharp, W.C. Nutritive value of warm-season grass hays for beef cattle and sheep; digestibility, intake and mineral utilization. *J. Anim. Sci.* 1984, *59*, 1582–1593.

Watermark Soil Moisture Sensor. Model 200SS. The Irrometer Company, INC. Riverside, CA.

Wilson, J. R., and D. J. Minson. "Prospects for improving the digestibility and intake of tropical grasses." *Tropical Grasslands* 14.3 (1980): 253-259.

Xu, Bingcheng, Fengmin Li, Lun Shan, Yongqing Ma, Nobumasa Ichizen, and Jin Huang. "Gas Exchange, Biomass Partition, and Water Relationships of Three Grass Seedlings Under Water Stress." *Weed Biology and Management* 6 (2006): 79-88. Web.

Yamori, Wataru, Kouki Hikosaka, and Danielle A. Way. "Temperature Response of Photosynthesis in C_3, C_4, and CAM Plants: Temperature Acclimation and Temperature Adaptation." *Photosynthesis Research* 119 (2013): 101-17. Web.

Youngner, V. B., and C. M. McKell. "Chapter 21- Physiology of Defoliation and Regrowth." *The Biology and Utilization of Grasses*. New York: Academic, 1972. 292-303. Print.

Youngner, V. B., and C. M. McKell. "Chapter 22- Defoliation in Relation to Vegetative Growth." *The Biology and Utilization of Grasses*. New York: Academic, 1972. 304-17. Print.

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