Evaluation of Cover Crops as an Alternative Forage Source for Beef Cattle

by

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Abstract

Grazing of cool-season cover crops has been shown to be a viable tool for extending the grazing season while mitigating environmental risks associated with row-crop farming systems. Grazing cover crops is not novel, but most recent information available on this practice focuses on soil health as opposed to forage production and animal performance. A 3-yr study was conducted in Headland, AL to evaluate the effects of cattle removal date on steer performance, forage biomass, and forage nutritive value in a grazed cover crop system. Twelve 0.62-ha pastures were established in a forage mix consisting of 'Cosaque' oats (*Avena strigose)*, 'FL401' cereal rye (*Secale cereal)*, 'AU Sunrise' crimson clover (*Trifolium incarnatum)*, and 'T-raptor' brassica (*Brassica napus* × *B. rapa*) and randomly allocated to be grazed through either mid-February (FEB), mid-March (MAR), or mid-April (APR) with an ungrazed control (CON). Three tester steers were randomly assigned in each paddock based on BW with the exception of CON. Put-and-take steers were added as needed to maintain a forage allowance of 1 kg DM/1 kg BW. Differences in forage biomass were detected between CON and FEB ($P < 0.001$), CON and MAR ($P < 0.001$), and CON and APR ($P < 0.001$). A difference in forage crude protein (CP) concentration was detected between MAR and CON ($P < 0.02$). No differences in animal performance were detected, and multiple regression analysis indicated that forage NDF concentration had the greatest influence on ADG of forage quality and stocking parameters. Results indicate that grazing of cool-season annual cover crops can reduce winter supplementation needs for cattle but may not be as advantageous when managed under continuous grazing for stocker cattle production. An additional study conducted at the Auburn University Ruminant Nutrition Laboratory evaluated the digestibility, Volatile Fatty Acid (VFA) production, and methane (CH_4) production of cool-season cover crops harvested at the beginning of either January (JA), February (FE), March (MA), or April (AP). The objective of this study was to determine if forage digestibility and subsequent products of digestion differed as forage physiology changes within a growing season. Samples were digested *in vitro* for either 2, 4, 8, 24, or 48 h. Cover crops harvested in JA had greater *in vitro* dry matter digestibility (IVDMD) than FE ($P = 0.009$), MAR ($P = 0.008$), and AP ($P = 0.01$) following 48-h digestion. No difference in total VFA production were present, but JA harvested forages produced less CH_4 than FE ($P = 0.01$), MA ($P = 0.003$), and AP ($P = 0.01$). Data from both studies indicate that cool-season annual cover crops can be a suitable grazing crop for beef cattle. Optimum grazing management strategies are not fully known, however.

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Acetate	(A)
Association of Official Analytical Chemists	(AOAC)
April forage harvest	(AP)
April removal	(APR)
Body condition score	(BCS)
Body weight	(BW)
Butyrate	(B)
Cation exchange capacity	(CEC)
Cell wall constituents	(CWC)
February forage harvest	(FE)
February removal	(FEB)
Glucosinolates	(GSL)
Greenhouse gases	(GHG)
Hydrogen	(H^+)
In vitro acid detergent fiber digestibility	(ADFD)
In vitro dry matter digestibility	(IVDMD)
In vitro organic matter digestibility	(IVOMD)
In vitro neutral detergent fiber digestibility	(NDFD)
January forage harvest	(JA)
March forage harvest	(MA)
March removal	(MAR)
Methane	(CH_4)

Nitrogen	(N)
No grazing	(CON)
Organic matter	(OM)
Propionate	(P)
Pure live seed	(PLS)
Soil organic carbon	(C)
Soil organic matter	(SOM)
Total digestible nutrients	(TDN)
Volatile fatty acids	(VFA)
Water	(H_2O)

Chapter 1: Literature Review

1.1 Introduction

The need for a sustainable and consistent food supply continues to grow as the world population increases. Technological advancements have brought forth an age which fewer people live in impoverished settings and thus have more disposable income available for food products (Ivanic and Martin, 2018). These advancements in technology have also contributed to increased urbanization and a greater consumer dependency on large-scale food production by consumers (Franzluebbers, 2007; De Baets et al., 2011). In 1960, each US farmer supplied food for 26 people and in 2012 this number increased to 166 (American Farm Bureau, 2022). Advances in the efficiency of crop harvest, preservation, and transportation have allowed this transition to occur, creating added pressure on production systems to generate enough food to feed a consumer base that is growing in size and dependency.

Over the last 100 years, the Southeast has been a highly productive region for crop and livestock production. It is estimated that approximately 42.5 million ha or 33% of the total land in the Southeast is used for agricultural purposes (Franzluebbers, 2007). This region of the country is capable of producing large cash crops such as cotton (*Gossypium hirsutum*), peanuts (*Arachis hypogaea*), corn (*Zea mays*), and tobacco (*Nicotiana tabacum*) (Anderson, 1956). Along with these cash crops, the climate and soil types of the Southeast are very conducive to produce many different forage species necessary for production of beef cattle and other pasture-based livestock.

Although agricultural cropland is just a small portion of the total landmass of the US, it is leaned upon heavily in terms of food and fiber production. Both global and domestic consumers depend on production of US agricultural products to live. As a result of urbanization and suburbanization, increases in demand for plant and animal food products will not be met solely by increased area available for crop production (Tian et al., 2021). This issue, as well as increased concerns from consumers for environmental sustainability, create a challenge for crop and livestock producers alike to create more environmental-friendly agricultural products with fewer resource inputs. Increased demand and diminishing land supply has led producers in the Southeast to diversify their on-farm operations by incorporating integrated crop-livestock systems into their management plans (Franzluebbers, 2007).

1.2 Importance of Cover Crops

1.2.1 History and benefits of cover crops

Cover crops have been used throughout agricultural history until the 20th century when the technological and Green Revolution reduced their use due to the perception that they were no longer needed in cropping systems (Franzluebbers, 2007). Furthermore, as technology has advanced, a shift from subsistence farming to large-scale commercial farming has occurred, and as a result, management practices have transitioned towards monoculture cropping systems and a large reliance on synthetic soil fertility and pest management (Franzluebbers, 2007). As a result, livestock were removed from cropping systems. These changes in land management pivoted operational goals to generating maximum product output and profit (Danhof, 1969). Research has shown over time that monoculture crop management creates many negative environmental impacts including increased pest infestation, nutrient runoff, increased incidence of plant disease, and herbicide-resistant weeds (Altieri, 2009). These negative effects have led to production settings with potential for severe crop losses, which has led to introduction of plant diversity back into cropping systems to mitigate these problems. One effective way to introduce plant diversity is by using multi-species cover crops during the fallow season (Fageira et al., 2005).

Cover crops provide many production advantages for producers through mitigation of environmental risks such as soil erosion (Langdale et al., 1990), nutrient leaching and runoff (Li et al., 2006), and pest and weed encroachment (Creamer and Baldwin, 2000) that result from multiple plant-soil interactions that greatly benefit overall health and structure of cropland soils (Franzluebbers, 2007). Cover crops are often an alternative or a combination of alternative forages planted through either conventional or minimum tillage. Plants selected for cover crops are often not valued as cash crops, but have the potential for high biomass production, atmospheric nitrogen (N) fixation, and soil organic matter (SOM) accumulation. As a result, their purpose is to provide support of the following cash crop and are therefore planted during the off-season of the cash crops. Cover crop should persist throughout the off-season; however, their residues typically persist through the crop growing season, assisting in the mitigation of these environmental risks year-round (Lu et al., 2000). By minimizing or fully eliminating the occurrence of fallow ground, cover crops are able to act as a layer of protection for the soil that assist in water retention and filtration, nutrient recycling, carbon (C) sequestration, and soil N accumulation (Fageria et al., 2005).

Cover crops often include forages that are highly productive during a short window and provide one or more ecological benefits to the soil profile. Cover crops can be monocultures of grasses, legumes, or brassicas, but they often include a combination of these three forage families (Drewnoski et al., 2018). Each plant family has specific qualities that are beneficial to soil health. Grasses used in cool-season cover crops are typically small grain species such as wheat (*Triticum aestivum*), cereal rye (*Secale cereale*), and oat (*Avena sativa*). Grasses are the greatest producer of biomass in cover crop systems with the purpose of providing soil cover and increasing water infiltration (Franzluebbers and Stuedemann, 2015). Legumes used include crimson clover (*Trifolium incarnatum*), red clover (*Trifolium pratense*), and hairy vetch (*Vicia villosa*). These legumes provide additional aboveground biomass but are included to capture atmospheric N and convert it into a plant-available form, thus reducing synthetic N fertilizer needs. Brassica species include varieties of turnips (*Brassica rapa*), rapeseed (*B. napus*), and radishes (*Raphanus sativus*). Brassicas are important because of their ability to provide early-season biomass, act as a soil biofumigant for disease and weeds, and contribute to belowground SOM via their primary taproot (Dillard et al., 2018). Use of these plant species in combination increases the positive impact the cover crop has on the soil and the environment.

1.2.2 Nitrogen Recycling and Accumulation

One of the benefits to utilizing cover crops in row crop farming operations is their ability to increase the efficiency of N use and retention in the soil (Fageria et al., 2005) that occurs through many different biological mechanisms including organic N storage within the soil, reduced nitrate leaching as a result of increased soil aggregates, and transformation of N into less water-soluble forms (Fageria et al., 2005). Cover crops that include leguminous plants increase the presence of N in the soil due to fixation of atmospheric N within the soil by legumes that have a symbiotic relationship with Rhizobia bacterial species present in nodules along the roots (Ladha et al., 2004; Fageria et al., 2005).

Non-leguminous plants can also positively influence soil nitrate retention and N application in row crop soils. Bauer and Roof (2004) found that the use of use of crimson clover, cereal rye, and cereal rye + crimson clover mixture cover crops had a reductive effect on N needs in the subsequent cotton crops. Clover cover crops stored up to 516 kg N/ha in the soil, while cereal rye and cereal rye + crimson clover mixtures stored up to 438 kg N/ha and 421 kg N/ha, respectively (Bauer and Roof, 2004). Nitrogen accumulated by cover crops can be highly beneficial from both economic and ecological perspective. However, any N that is stored in the soil is not immediately available for plant use. Once organic N is stored as SOM, soil bacteria then convert this N to an inorganic form through mineralization before it will be available for uptake by the cash crop (Fageria et al., 2005). When legumes are used, it can be expected that they provide up to 40 ppm of N (60 kg/ha N) available for the subsequent crop as NH_4^+ and NO_3^- (Ebelhar et al., 1984).

In minimum tillage and no-till systems, the use of grass cover crops has been shown to be beneficial. Degradation of plant residues left from grasses can reduce nitrate leaching as residues incorporate into the soil profile (Bauer and Roof, 2004). Plant residues become SOM as they are naturally degraded in the soil. Increased presence of SOM allows for greater water-holding capacity in the soil (Bauer and Roof, 2004). Use of both legumes and grasses allows for accumulation of soil organic N to occur and provides increased soil structure so that nitrates are able to be converted to plant-usable, inorganic forms while reducing nitrate leaching (Franzluebbers, 2007).

Additional N that is accumulated into the soil profile following use of a legume is often referred to as N credits (Blevins and Frye, 1993). A typical N credit following a cover crop containing an annual legume is 75 – 1,000 kg N/ha (Blevins and Frye, 1993; Vyn et al., 1999). Nitrogen credits at these levels can greatly impact the overall productivity of a subsequent cash crop, as well as decrease the cost of production attributed to N fertilizer application (Crews and Peoples, 2004). However, accumulation of soil N should be considered in relation with accumulation of soil organic C. Studies have shown that instances in which large amounts of C are present in the form of cover crop residues, subsequent crops can have reduced yields (Johnson et al., 1998). This is due to an abnormally high C:N ratios within the soil and in turn, high levels of soil N immobilization (Francis et al., 1998). If mineralization of N does not occur at a similar rate to N immobilization, the potential for N deficiencies increases reducing future crop yields.

1.2.3 Increasing Soil Organic Matter

Soil OM refers to the amount of C within the soil profile. Increased SOM provides many agronomic and environmental benefits. Organic matter within the soil increases soil stabilization, aeration, water holding capacity, and fertility (Allison, 1973; Bauer and Black, 1994). Cover crops have an additive effect on SOM in minimum and no-till systems (Poeplau and Don, 2015). Tillage of soil is the most common cause of C and N losses due to volatilization (Conant et al., 2007). Because cover crops can be established with minimum tillage, they are able to add to SOM levels with little to zero losses of C through volatilization. This management technique has shown to be favorable in reducing many agronomic risks associated with conventional tillage methods such as soil aggregate degradation (Grandy et al., 2002). Increased SOM also has a positive relationship with water infiltration, root growth, and hydraulic conductivity of soils (Fageria et al., 2005). The SOM also has a direct impact on soil characteristics such as soil pH, cation exchange capacity (CEC), and buffering capacity (Fageria et al., 2005). dos Santos Cordeiro et al. (2021) investigated the effects of different cover crop mixtures on CEC compared with fallow ground. It was found that fallow ground had up to 20% lower CEC than various cover crop treatments. The authors attributed decreased CEC to increased water holding capacity, thus a reduction in leaching in cover crop treatments.

Soil OM is also an important reservoir for atmospheric C (Follett, 2001). In instances where conventional tillage is used, any stored C within the soil is released into the atmosphere via volatilization and respiration. Conservation tillage and implementation of cover crops allow for increased soil C sequestration, with minimal release of CO_2 back into the atmosphere. La Scala Jr et al. (2006) compared C release from soils following no-till, reduced tillage, and conventional tillage. Twenty-seven days post treatment, no-till and reduced tillage released less C into the atmosphere than conventional tillage (0.77, 1.22, and 2.83 g of CO_2/m/h, respectively). Nascente et al. (2013) found that no-till cover crops of pearl millet (*Pennisetum glaucum*) maintained greater levels of soil organic C over a three-year period than conventional tillage in multiple different soil fractions (1.94% vs. 1.79%, respectively).

1.2.4 Erosion Control

Cover crops provide an effective mitigation tool for soil erosion through off-season ground cover and increased soil aggregate formation due to plant root development (De Baets et al., 2011). Grasses, legumes, and brassicas have complementary growth patterns and tend to not compete with one another when grown together (Dillard et al., 2018). Differences in plant morphology, specifically root development, allow for increased soil aggregate development (De Baets et al., 2011). Legumes and brassicas develop a primary tap root, whereas grasses have a more fibrous root system (Soreng et al., 2015). Increased soil aggregates as a result of multiple root types being present leads to greater efficiency of nutrient retention and utilization by minimizing losses due to leaching. De Baets et al. (2011) found that cover crops containing only grasses exhibited less water erosion than cover crops containing only brassicas (0.4 vs. 3.75 units, respectively) due to the ability of fibrous root systems to enhance soil stability.

1.3 Cover Crop Species

1.3.1 Cereal Rye

Cereal rye is a widely used small grain throughout the US. Cereal rye is known for accumulating large amounts of biomass with moderate forage quality. As opposed to other small grain species, cereal rye is more tolerant to acidic soils with moderate cold tolerance (Ball et al., 2016). Cereal rye can be used as a monoculture grazing crop, but it also complements other forages such as clovers and annual ryegrass (*Lolium multiflorum*) (DeRouen et al., 1991; Mullenix et al., 2014; Dubeux et al., 2016). Cereal rye has an early growth pattern with high biomass potential making it a suitable species for use in a cover crop mixture (Franzluebbers and Stuedemann, 2014).

Compared with other varieties of cereal rye, 'FL401' is more prone to early plant maturation, but it is tolerant to acidic soils (Dubeux et al., 2016). FL401 has traditionally been used as a high-yielding cover crop. Early biomass yield is beneficial for soil health as it provides early and lasting ground cover (McGee, 2020). This cultivar of cereal rye is also persistent in seedling vigor (>85%) and moderately resistant to frost damage (95.3% winter hardiness). In northern Florida, Dubeux et al. (2016) investigated the use of FL401 as part of a mixture with annual ryegrass compared with oat mixed with annual ryegrass and triticale (×*Triticosecale*) mixed with annual ryegrass. The authors found that mixtures containing FL401 had greater initial herbage biomass, but biomass accumulation rates declined later in the growing season due to the cereal rye transitioning to the reproductive stage of maturity. Mixtures containing FL401 had lower *in vitro* OM digestibility (IVOMD) than the mixtures with oat and triticale. These data indicate that FL401 can be useful for increasing forage yield at the beginning of the grazing season, but less effective as plants become mature and digestibility decreases in mid- to late season.

1.3.2 'Cosaque' Oat

Oat is a highly adapted small grain in the Southeast. It is known for fall and early spring biomass production, as well as good palatability (Ball et al., 2016). Although it is capable of producing large amounts of herbage mass with desirable forage quality, it is the least cold tolerant of the small grain species (Ball et al., 2016). Like other small grains, this forage can serve as a stand-alone forage crop, but it also can be used in diverse forage mixtures (Beck et al., 2014). In cover crops, oat can be used as an early growth forage that provide biomass accumulation and grazing if desired.

‘Cosaque’ oat is a variety of black-seeded oat that are popular for use as cool-season cover crops. Variety trails conducted by the USDA-ARS in Coffeeville, Mississippi showed that Cosaque had excellent field emergence (>85% seedling vigor) and excellent winter hardiness (97%) (Richard and Allison, 2020). Ryan et al. (2021) investigated the use of Cosaque as a finishing diet for meat-type goats compared with annual ryegrass and crimson clover mixtures and a commercial concentrate feed. Nutrient concentration of this forage was comparable to the annual ryegrass/clover mixture, with oat having a 15.0% crude protein (CP) and a 30.3% neutral detergent fiber (NDF), and the annual ryegrass/clover mixture having a CP of 22.4% and NDF of 29.8%. In this study, oat was more effective for producing with 11% greater average daily gain (ADG) than the commercial supplement.

1.3.3 ‘AU Sunrise’ Crimson Clover

Crimson clover is an annual legume that can serve many purposes. This legume is known for its high CP concentration and forage digestibility, along with high biomass potential (Ball et al., 2016). Crimson clover is best adapted to upland, sandy-loam soils and is known for having the greatest rate of production in the spring (Mullenix and Rouquette, 2018). Like other annual clovers, crimson clover is often used in mixtures with other forages such as annual ryegrass. Use of crimson clover as a monoculture is not as common in grazing scenarios because of its propensity to cause bloat in grazing ruminants (Clarke and Reid, 1974).

‘AU Sunrise’ was developed by Auburn University, the Alabama Agricultural Experiment Station, and the USDA-NRCS (Mosjidis et al., 2000). It was developed to be earlier maturing than pre-existing varieties of crimson clover, while still maintaining yield and forage quality potential. Upon development it was found that AU Sunrise flowered 5 to 18 days earlier than the next earliest maturing variety (Mosjidis et al., 2000). The authors suggested that this variety would be ideal for use in cover crops because of its tendency to mature earlier in the growing season. Terrill et al. (2004) determined whether goats preferred specific varieties of clovers in a cafeteria-style grazing study and found that AU Sunrise was similar in nutrient composition to other commonly used crimson clover varieties (18.5 – 24.2% CP and 25.3 – 32.2% NDF) and selected for grazing between 10 – 75% over other clovers depending on season. The combination of early maturity and acceptable grazing preference indicate that AU Sunrise crimson clover can be beneficial to grazed cover crop systems.

1.3.4 ‘T-raptor’ Brassica

Use of forage brassica species is an effective management tool for generating early cool-season forage biomass accumulation (Dillard et al., 2018). Other cool-season forages such as small grains, clovers, and annual ryegrass can be extremely beneficial for cover crops and grazing, but all these species have peak growth following January 1. Traditionally, brassica forage species consist of rapeseed, radish, and forage-type turnips.

‘T-raptor’ (*B. rapa* subsp. *rapa* ×*B. rapa* L.) is a hybrid of turnip and rapeseed and has been shown to be a high yielding forage-type, brassica hybrid. Denman et al. (2021) found that T-raptor could be effectively established in both conventional and minimum tillage systems. Planting date influenced total forage yield with later planting dates having up to 94% less total forage production (4481 vs 270 kg DM/ha) than earlier planting dates. Nutritive values of T-raptor in this study were acceptable and provided comparable values as other cool-season annual forages. Crude protein concentration ranged between 17.3% and 25.4%, wheras total digestible nutrients (TDN) values ranged from 64% to 78.6%. T-raptor is also resilient to grazing and has been shown to produce regrowth following simulated grazing (Simon et al., 2013). T-raptor initially produced 1,454 kg DM/ha of forage biomass. Following simulated grazing, it produced 454 kg DM/ha of regrowth. These data indicate that T-raptor can be sufficient in producing adequate herbage biomass to serve as both a soil protectant and grazed forage crop.

1.4 Grazing of Cool-season Annual Forages with Cattle

1.4.1 Forage Quantity and Quality

Cool-season annual cover crop monocultures and mixtures were developed with biomass production as a top priority. To provide ecosystem services, cover crops must produce adequate aboveground biomass to protect soil from climatic events such as rain or drought (Plainisich et al., 2021). This plant biomass could potentially serve as a secondary grazing crop for livestock such as beef cattle. Establishment, plant selection, and grazing intensity are thought to be three of the most significant drivers of forage accumulation (Edwards and Chapman, 2011; Franzluebbers and Stuedemann, 2014). However, research has shown that establishment method and cover crop species had no effect on overall forage yield (Franzluebbers and Stuedemann, 2014). Conventional tillage and no-till practices produced similar forage biomass across a three-year period in cover crops that included cereal rye and a red and white clover (*Trifolium repens*) mixture (4910 kg DM/ha vs. 4440 kg DM/ha), as well as cereal rye/annual ryegrass mixtures (7050 kg DM/ha vs. 5890 kg DM/ha) (Franzluebbers and Stuedemann, 2014). Utilization of these pastures resulted in similar plant residues after grazing termination. Although no differences in yield were detected, conventional tillage crops had 38 more grazing days than no-till crops in the third year. The authors attributed this to earlier germination due to greater seed to soil contact in the conventional tilled system (Franzluebbers and Stuedemann, 2014). Other studies reinforce that forage mixtures can provide greater yields than monocultures. Sanderson et al. (2018) reported that the use of cool-season annual mixtures produced between 30 – 60% greater dry matter (DM) yield than monocultures of the same species. This study was conducted in North Dakota, which is cooler and more arid than the Southeast, and for this reason spring planting, not fall, was used. The differences in climatic conditions could potentially have contributed to a greater growth potential for brassicas and legumes as opposed to fall-planted mixtures that are subject to frost damage and possible winter kill.

Different plant species combinations will produce different yields. It was found that combinations of small grains, legumes, and brassicas would produce upwards of 5000 kg DM/ha when left ungrazed (Villalobos and Brummer, 2017). Although production was less than from small grain monocultures used in the study, forage mixtures produced adequate forage biomass while also providing environmental services such as N recycling and increasing soil structure. This study also analyzed the nutritive value of different forage combinations and found that including brassicas and legumes in a forage mixture resulted in greater CP concentration (18% vs. 14%, respectively) and less NDF concentration than small grain monocultures (22% vs. 57%, respectively) (Villalobos and Brummer, 2017). These data indicate that inclusion of brassicas and legumes provided additional forage quality benefits to a sward mixture. Mason et al. (2019) reported that overseeding of Eastern gamagrass (*Tripsacum dactyloides*) with either cereal rye or a combination of cereal rye and red clover had no effect on herbage accumulation, CP concentration, or *in vitro* dry matter digestibility (IVDMD) in western Alabama. Deak et al. (2007) investigated whether species inclusion had influence on the nutritive value of different forage mixtures and found no difference for CP or IVDMD percentage between 2-species mixtures consisting of one perennial grass and one clover versus a 9-species mixture containing multiple grass and clover species. The authors concluded that the lack of differences can be attributed to dominance of either orchardgrass (*Dactylis glomerata*) or tall fescue (*Schedonorus aruninaceus*) in the sward. It was also determined that clovers did account for over 85% of variation in forage CP concentration among mixtures, suggesting that whereas they may not attribute to forage biomass, their inclusion is important in providing a high-quality forage to livestock.

1.4.2 Grazing monoculture forage swards

Cool-season annuals have become a staple winter and spring forage crop for cattle producers throughout the Southeast (Dillard et al., 2018). Agronomic characteristics such as increased seedling vigor and rapid growth rate, paired with high forage quality make cool-season annuals a desirable forage crop for both cow-calf and stocker operators. Cool-season annual forages include many different plant species (small grains, annual ryegrass, brassicas, and legumes). These forages are great tools for graziers in the Southeast, as they can extend the grazing season well into the winter and early spring when properly managed (Dillard et al., 2018).

Along with producing additional above-ground biomass throughout the winter and spring, cool-season annuals provide a nutrient-dense forage base that can be established in a variety of different ways (Mullenix and Rouquette Jr, 2018). These forages can be advantageous for cow-calf and stocker operators, but their management can differ depending on operational goals. In cow-calf operations, cool-season annual forages are often used as a substitute for hay and supplemental concentrate feed (Rouquette Jr, 2017). With this objective in mind, the primary measure of success for grazing cool-season annuals with cows is often the addition of annual grazing days (Mullenix and Rouquette Jr, 2018). This often reduces costs of winter feeding and the amount of labor and equipment needed to provide cattle with optimal nutrition in the winter months. In addition to providing additional grazing days, the use of cool-season annuals can result in increased cow performance compared with hay alone. Prevatt et al. (2017) showed that the cost of maintaining a cow over the winter in Southern Alabama was reduced by $100/hd/year by using cool-season annuals in addition to hay and supplement, compared to hay and supplement only. DeRouen et al. (1991) investigated the effects of interseeded wheat (*Triticum aestivum*) and rye paired with crimson clover and arrowleaf clover (*Trifolium vesiculosum*) on cow-calf performance compared with feeding hay and supplement. This study found that use of cool-season annuals resulted in greater calf weaning weights (225 vs. 212 kg, respectively), cow body weight (BW) (509 vs. 487 kg), and calf weight/454 kg cow weight (201 vs. 195 kg) than feeding of supplemental bahiagrass (*Paspalum notatum*) hay and a commercial 30% protein grain supplement. This increase in cattle performance paired with a potential for decreasing labor make grazing cool-season annual forages a good option for graziers in the Southeast.

A variety of forage monocultures provide adequate grazing crops for growing cattle. Wheat, oat, rye, and triticale all serve as adequate grazing crops. Forage yield and animal performance among these species are comparable. Beck et al. (2007) reported that grazing of oat, rye, and wheat resulted in similar ADG (1.10, 1.17, and 1.14 kg/d, respectively), BW gain per hectare (385, 433, and 484 kg/ha, respectively), and grazing days per hectare (535, 560, and 581 d, respectively). Mullenix et al. (2014) compared the use of wheat and triticale with annual ryegrass as grazing crops for stocker cattle. Three test steers were stocked per 1.42-ha paddock to assess individual animal performance. Additional put-and-take cattle were added to maintain forage biomass at 1,500 to 2,000 kg DM/ha. When planted in a monoculture, wheat pastures were capable of maintaining a greater stocking rate than both annual ryegrass and triticale. However, grazing of annual ryegrass resulted in the greatest ADG of the three forage treatments at 1.51 kg/day followed by wheat (1.36 kg/day) and triticale (1.23 kg/day). This study also concluded that overall animal production/ha was not solely attributed to ADG. Grazing days also plays an important role in achieving total gain in a grazing system. Total gain is a more useful measurement for animal production per land unit because it accounts for individual animal gain as well as stocking capabilities and grazing tolerance of a forage crop. Wheat had the greatest grazing days per hectare at 497. Triticale and annual ryegrass followed at 415 and 406 grazing days/ha, respectively. This relationship shows that overall animal production per land unit is not solely a function of forage quality, but a dynamic relationship between forage quality and forage availability.

1.4.3 Grazing Mixed-Species Swards

Although small grain crops can provide acceptable cattle performance as monoculture crops, the use of forage mixtures provides additional benefits in terms of number of grazing days per growing season (Beck et al., 2007). Marchant et al. (2019) evaluated stocker cattle performance when grazing wheat, triticale, and annual ryegrass as mixtures. This study maintained a forage allowance of 1 kg DM/1 kg BW using the put-and-take method to ensure that forage availability did not impact cattle performance. Cattle grazed paddocks of either wheat and annual ryegrass, triticale and annual ryegrass, or wheat, triticale, and annual ryegrass. It was found that no mixture provided any advantage over another in terms of forage yield, grazing days, or stocking density. Steers grazing these pastures also had similar performance with ADG ranging from 1.39 – 1.49 kg/d. This study showed that ternary mixtures of small grains and annual ryegrass provided no advantage over binary mixtures. Similar research in Argentina reported that heifers grazing oat pasture had less ADG (0.67 kg/day) than previously discussed forage species and mixtures (Arelovich et al., 2003). However, Beck et al. (2007) found that oat generated similar cattle gains as other small grain monocultures such as wheat and rye. Holstein heifers grazing annual ryegrass cover crops to different residual plant heights were found to gain 0.34 – 1.05 kg/d with higher residual heights resulting in greater ADG (Planisich et al., 2021). This data confirms the relationship between plant availability, forage allowance, and animal performance (Rouquette, 2017).

Blending of small grains with clovers and brassicas can be advantageous from both cover crop and livestock grazing perspectives. However, data concerning the use of clovers in cool-season annual forage mixtures is inconsistent. In Arkansas, Beck et al. (2012) examined the effects of white clover inclusion into wheat and annual ryegrass pastures in place of N fertilizer. Although steers on synthetically fertilized pastures outperformed steers grazing pastures with white clover, the economic return per hectare was greater for the clover paddocks due to the reduced establishment cost resulting from reduced synthetic fertilizer needs. Steers on white clover paddocks were also able to acquire 10 more grazing days than those that grazed pastures treated with synthetic N. Addition of cereal rye and crimson clover to ‘Coastal’ bermudagrass (*Cynodon dactylon*) pastures was found to yield greater calf gains (236 kg/ha) than the overseeding with only clovers (184 kg/ha) or annual ryegrass (188 kg/ha) in South Alabama (Hoveland et al., 1978). This same study found that addition of a cereal rye and crimson clover together extended the grazing season by three months compared with not planting anything. Gunter et al. (2012) found similar results in terms of calf performance in Arkansas. The authors examined the effects of different cool-season annual forage mixtures on cow reproductive efficiency and calf growth rates. Cows were allowed to graze dormant bermudagrass pastures overseeded with either wheat and annual ryegrass alone or different combinations of wheat, annual ryegrass, and either red, crimson, or white clover. Although there were no differences among treatments for cow reproductive performance or body condition score (BCS), it was found that treatments including clovers had greater calf weaning weights than those without them (212 and 173 kg, respectively).

1.4.4 Stocking Density and Rate

Stocking rate and stocking density are two essential measurements of grazing pressure that have great impacts on the success of a grazing program. Although these terms are regularly used interchangeably, they do have differences that translate to management of forage biomass production. Stocking rate refers to the mean concentration of grazing animals over a given period. Stocking density refers to the concentration of animals at a specific timepoint. Stocking density is more appropriate for matching kg BW to kg DM throughout a grazing season as forage production changes, whereas stocking rate is a better benchmark for grazing pressure throughout an entire season.

Maintaining appropriate stocking densities throughout the grazing season can be a challenge to many livestock producers. The relationship between soils, plants, and animals is dynamic and is a balance of give and take of nutrients. Soils provide nutrients to forages, while forages provide nutrients to animals. Grazing livestock recycle nutrients captured in forage biomass through urination and defecation back to the soil. Management of this relationship comes in two forms: 1) extensive management that alters the extent and efficiency at which resources are used through temporal and spatial distribution of plants and animals; and 2) intensive management that depends on additional energy and resource inputs (Heitschmidt and

Stuth, 1991). These two systems are often exclusively used for either native pastures or introduced pastures. Native pastures require less inputs but are more sensitive to stocking density and grazing days. Introduced forages are highly productive and can tolerate greater grazing pressure, but they must have additional resource inputs to maintain production over time because they are not native to the region (Fleischner, 1994; Ball et al., 2016). An understanding of optimal stocking rate is necessary for these systems in order to maintain ecological sustainability. If excess grazing pressure is used, forages will have reduced root growth resulting in reduced energy reserves (Edwards and Chapman, 2011), and the resulting shortage in forage biomass will cause a decrease in cattle performance due to limitations on DM intake (Inyang et al., 2010). Alternatively, if inadequate grazing pressure is applied, cattle performance will decrease due to increased plant maturity and coincidental increases in plant fiber fractions and reduction in leaf-to-stem ratios which reduces digestibility, available energy, and CP (Aguiar et al., 2014).

Previous studies have used put-and-take cattle to maintain forage allowances of 1 kg DM per kg BW (Marchant et al., 2019; Mullenix et al., 2014). This method adjusts stocking density based on the productivity of the forage, while always maintaining tester animals on pasture to evaluate animal performance (Beck et al., 2014). A similar method of stocking pastures can be found in Pinchak et al. (1996). In this study, researchers stocked different wheat cultivars based upon forage availability at the beginning of the season. This stocking density was maintained until the forage crops began to reach the reproductive phase of their life cycle. To keep up with this rapid growth, additional steers were placed on pasture late in the grazing season to maintain the vegetative phase of the plant. Alternatively to managing residual forage throughout a grazing season using stocking density, other studies have assessed grazing effects based on reaching a certain percentage of forage harvest (Franzluebbers and Stuedemann, 2008b; Franzluebbers and Stuedemann, 2015).

Although effective in managing when to stop grazing, the amount of time between harvest and termination could potentially affect how much forage residual is available at termination. In grazed cover crop systems, this method could result in too little forage residual at termination if forage growth is not rapid enough. Some researchers have chosen to stock pastures according to total BW per hectare for grazing of cover crops (Kelly et al., 2021). The authors used variable stocking densities based on individual producer and location. This study had stocking densities ranging from 307 to 1,052 kg BW/ha. Use of two separate stocking densities based on season have been shown to be a viable option for managing stocking. Steers grazing winter wheat were stocked at 1.6 ha/steer in winter and 0.8 ha/steer in spring (Beck et al., 2014). Once fall steers grazed the wheat crop to where there was less than 1,000 kg/ha of forage available they were removed (Redmon et al., 1995). Pastures were then allowed to rest and had a second group of steers placed on pasture once spring forage biomass accumulation was greater than 1000 kg/ha again (Beck et al., 2014). Seasonal stocking density was changed in anticipation of greater forage biomass accumulation that occurs in spring as compared to fall.

1.4.5 *Effects of grazing cover crops on cash crop performance*

The primary purpose of cover crops is to improve soil health leading to increased cash crop yields (Fageira et al., 2005). Many producers are concerned that grazing cover crops will reduce their effectiveness of cover crops. Research has shown that when row crop fields that were managed as grazed cover crops, un-grazed cover crops, or left fallow, fallow fields had the greatest wheat grain yield, whereas grazed and un-grazed fields were not different (3700, 2900, and 2800 kg/ha, respectively) (Kelly et al., 2021). Although this study suggests that leaving fields fallow may increase crop yield, the study was only conducted for three years. Franzluebbers and Steudemann (2014) have shown that cash crop yield was more dependent on tillage method than cover crop grazing management. The authors reported that no-till corn crops had greater yields (263 and 240 g/m) than conventionally tilled corn (134 and 56 g/m) when grown after grazed and ungrazed cover crops. Soybeans (*Glycine max*) grown in this study showed similar results with yield being the same in both grazed and un-grazed treatments (Franzluebbers and Steudemann, 2014). Tracy and Zhang (2008) also found that grazing of cover crops on conventionally tilled fields resulted in greater corn yields (12 vs 10 Mg/ha) and also concluded that production of cattle and corn resulted in greater total value of land use than continuous corn production alone. Introduction of cattle to cropping systems has shown to have minimal negative effects and in some instances positive effects on cash crop yield (Tracy and Zhang, 2008). Presence of cattle provides both ecological and economic benefits such as increased nutrient cycling and increased farm income.

1.4.6 Economic Return from Grazed Cover Crops

Potential for environmental sustainability of grazed cover crops has been well studied over the past two decades (Clark et al., 2004; Tracy and Zhang, 2008; Franzluebbers and Steudemann, 2008a; Franzluebbers and Steudemann, 2008b; Kelly et al., 2021). However, the impact of grazing cover crops on economical sustainability of an operation has not been greatly investigated. Adoption of cover crop use was initially met with hesitation by producers due to increased production cost associated with crop establishment, management, and termination, with no immediate financial return (Bergtold et al., 2019).

DeLaune et al. (2020) found that including both monoculture and mixed-sward cover crops consisting of Austrian winter pea (*Pisum* sativum), hairy vetch, crimson clover, wheat, or a multi-species mixture increased seed costs ($819.35 vs $687.96/ha) but had no effect on net return ($384.89 vs 475.44/ha) in cotton systems in North Texas. The authors concluded that although no direct economic incentive was present, the use of cover crops provided environmental advantages to continuous-cropping systems without affecting economic return. Depletion of plant diversity in cropping systems has greatly reduced overall stability of cash crop farming operations. Inclusion of cover crops provides biogeochemical and ecological controls that contribute to long-term viability of cropping systems (Lemaire et al., 2014). Including cattle grazing into this scheme provides many ecological incentives, as well as a diversity in on-farm income.

Diversifying farming operations is becoming a more common substitute for intensive, monoculture farming because of its positive impacts on the environment (Lemeaire et al., 2014). However, development of integrated crop-livestock systems does not come without some added costs. Poffenbarger et al. (2017) found that including cattle grazing into a crop rotation resulted in similar returns ($370 – $1,200/ha) as that of traditional cropping systems because of the added infrastructure and labor needed to manage livestock. These data suggest that adding cattle production to a farming operation may not produce greater net returns. However, with continued use these additional costs would be spread over multiple growing seasons, increasing the system’s economic viability. More research is needed to determine if the same effects are present when cattle infrastructure and labor are already in place and accounted for in terms of operational budgeting.

1.5 Environmental Impacts of Grazing Cattle

1.5.1Effects of grazing cover crops on soil health

Grazing of cover crops has been thought to be detrimental to soil health but has been proven to be otherwise (Franzluebbers and Stuedemann, 2008a). Franzluebbers and Studemann (2008a) compared soil physical characteristics of different cover crop systems that were established through either conventional tillage or no tillage. These cover crops were then either assigned to be either grazed or ungrazed. Similar to the results seen by Balbinot Jr et al. (2011), the authors found that after 4.5 years, grazing only affected soil bulk density and soil compaction in the top sub-soil layer (1.02 and 1.08 Mg/m^3, respectively).

Concerns of cattle foot traffic affecting soil compaction in these systems has created hesitancy among producers and government cost-share agencies (Dillard, Personal Communication). Grazing of cover crops can have some effects on soil physical properties and possibly lead to soil compaction. However, recent data reinforce that when soil compaction effects are present, they are within the first 10 cm of the soil and have minimal effects on root development and potential yield of subsequent cash crops and cover crops (Franzluebbers and Stuedemann, 2008a; Balbinot Junior et al., 2011; Kelly et al., 2021). Kelly et al. (2021) reported when comparing grazed and un-grazed cover crops to fallow soil, it was found that grazing of cattle had no effect on soil compaction and that use of cover crops increased soil aggregate stability. Bulk density was greater in grazed and fallow fields than in un-grazed fields. Balbinot Jr et al. (2011) investigated the effects of grazing cool-season annual cover crops with and without N fertilization compared with an ungrazed mixed sward cover crop, seed-oil brassica cover crop, and volunteer vegetation. This study found that grazing increased soil compaction in the top layer of subsoil (0 – 5 cm) in the grazing treatment without N, suggesting decreased forage yield and increased trampling in comparison to the grazing treatment including N. The lack of difference in lower subsoil zones indicates that root growth of future cash or cover crops would not be inhibited by grazing with cattle.

Grazing of ruminant livestock on cover crops encourages rapid recycling of nutrients, while still providing the cover crops originally intended protective qualities (Franzluebbers, 2007). Storage of SOM, specifically organic C, can have highly beneficial effects on soil health and soil microbial activity (Poffenbarger, 2010). Sequestration of C from the atmosphere into soils also helps negate environmental risks associated with excess CO_2 generated via microbial fermentation in grazing livestock (Soussana et al., 2010). Anecdotes suggest that by reducing plant biomass accumulation because of grazing, nutrient recycling will also be reduced. However, research has shown that a crop rotation of corn and grazed oat accumulated 2 – 4% more organic C than all cropping systems except for perennial cool-season pastures over a four-year period (Tracy and Zhang, 2008). Comparisons of organic C sequestration between grazed and un-grazed cover crops found that in the first 3 cm of the soil profile, grazed winter cover crops had greater amounts of sequestered C than un-grazed, but the opposite was true in summer cover crops (Franzluebbers and Stuedemann, 2008a).

Nitrogen is also an important soil and plant nutrient that has been shown in both grazed and ungrazed cover crops to increase efficiency of use by 12 – 15% (Franzluebbers, 2007). Nitrogen is necessary for plant biomass production, but acquisition and dispersal of both organic (e.g., poultry litter) and inorganic (e.g., urea) N fertilizers are expensive. Nitrogen is also water soluble which, if not properly managed, could lead to negative environmental impacts through runoff and leaching. Unlike fallow fields, cover crops capture and recycle N in plant residues. Research has shown that an oat cover crop alone can be effective in reducing N leaching and runoff by up to 20% (Tracy and Zhang, 2008). Cover crops containing legumes are also effective at retaining and recycling N. Similar to C, it was thought that grazing of cover crops with and without legumes could potentially reduce the amount of N recycled in soil environments. Francis et al. (1998) found that cool-season cover crops grazed with sheep accumulated greater amounts of soil inorganic N than un-grazed cover crops, presumably because N produced by ungrazed crops was in an organic form that was unavailable for plant growth whereas manure from grazing animals was in an inorganic form and was therefore bioavailable for cover crop and the subsequent cash crop. Franzluebbers and Stuedemann (2008b) reported that grazing of no-till cover crops did not affect inorganic N at depths of 0 – 30 cm for either conventional or no-till systems. Although data from these two studies are conflicting, neither indicates that grazing of cover crops could potentially decrease the accumulation and recycling of organic or inorganic N at various depths within the soil.

1.5.2 Forage Digestibility and VFA Production

Forage feedstuffs make up the largest portion of the ruminant diet. Ruminants evolved over time to have the ability to utilize plant materials as their sole source of nutrition (Hofmann, 1989). Although seeds and grains can be part of the ruminant diet, the largest portion consists of fibrous materials. Fiber provides structural integrity for the plant and allows the plant to grow vertically. Ruminants are able to utilize OM from plants through a symbiotic relationship with rumen microorganisms that are capable of fermenting polysaccharides in the plant cell wall that are otherwise indigestible through animal enzymatic processes (Hungate, 2013). This relationship allows ruminants to use feed materials that other animals are incapable of digesting. The physiology of plants and proportions of different cell wall constituents have profound effects on the extent and rate at which digestion of plant materials will occur (Jung and Allen, 1995).

Although the terms cell wall and fiber are often used interchangeably, it is important to note that specific components of the cell wall act as dietary fiber and influence digestive kinetics and greenhouse gas (GHG) production (Jung and Allen, 1995). The cell wall comprises soluble and insoluble fractions. Soluble fractions include pectins, gums, and other organic acids. Insoluble fractions include cellulose, hemicellulose, and lignin. The ratio of total cell wall components to insoluble fractions differs between grasses and legumes. Mature grasses contain similar amounts of soluble cell wall contents and insoluble fiber, while mature legumes tend to have higher levels of soluble cell wall contents than insoluble fiber (Van Soest, 1994).

Lignin is known to play the greatest role in the degree that fiber is digested in the rumen (Jung and Deetz, 1993). Lignin is directly related to plant maturity and in turn the scope that nutrients are available in plants of different maturities. Weaver et al. (1978) investigated if changes in *in vitro* digestibility occurred in corn plant components throughout the growing season. In all plant parts except the grain, the total cell wall contents and lignin increase while total digestibility decreases as the plant matures.

As total digestibility of a feedstuff decreases, the total amount of energy available to the host animal decreases as well. Energy available to the ruminant is in the form of volatile fatty acids (VFA) with the two greatest produced VFA being acetate and propionate (Russell, 2002). Acetate is produced primarily via fibrolytic microbes that break down portions of the cell wall, whereas propionate is largely produced by amylotytic bacteria and syntrophic cross-feeding bacteria (Russell, 2002). Chaves et al. (2006) determined the effects of perennial ryegrass (*Lolium perenne*) maturity on total digestibility, as well as VFA production *in vitro*. Results confirmed those of Weaver et al. (1978), in that as cell wall contents increased total digestibility decreased. The authors of this study found that total VFA (1.79 vs 1.19 mmol/g DM), acetate

(1.12 vs 0.82 mmol/g DM), propionate (0.39 vs 0.25 mmol/g DM) and ratio of acetate to propionate (3.01 vs 3.47 mmol/g DM) did not change with increased plant maturity. The decreased rate of digestion for mature forages could potentially affect the extent of ruminal digestion compared to particle size and rumen turnover in some scenarios (Chaves et al., 2006). Ribeiro Jr et al. (2014) investigated the effects of plant maturity and storage method on *in vitro* digestibility and methane (CH_4) production in gamba grass (*Andropogon gayanus*), and it was found that more mature forages were less digestible than younger forages but showed no decrease in VFA production. Forage harvested at later dates did produce 8% more CH_4 than early harvested forage indicating that forage maturity can affect CH_4 production in the rumen.

Although forage maturity plays a large role in digestibility, it is not the sole determinant. Forage species used for grazing livestock can often be broken down into three taxonomic families (*Poaceae, Fabacea*, and *Brassicaceae*). These families are commonly known as grasses, legumes, and brassicas. These three families can be very complementary of one another in a production setting due to their differing growth habitats. These forages also have differences in physiology that can lead to differences in animal performance when grazed. There are key anatomical differences among the three families that translate to differences in digestibility and subsequent by-products of digestion in ruminant herbivores.

Short et al. (1974) investigated the digestibility of panicgrass (*Panicum sp.*), cereal rye, and mixed grass swards in comparison to browse species such as pussytoes (*Antennaria plantaginifolia*) and browse twigs using *in situ* methodology. This study found that grasses were less digestible than various browse species, including leguminous forbs. These results were attributed to increased proportions of lignin to cellulose and hemicellulose in the cell wall constituents (CWC). It was also found that as all plants increased in maturity, the difference in digestibility between plant species diminished. This was due to the increase in indigestible lignin levels within the plants.

1.5.3 Methane Production

Greenhouse gases (GHG) such as CO_2, N_2O, and CH_4 capture thermal energy from the sun's radiation and release it back into the atmosphere (DeRamus et al., 2003). Naturally occurring GHG are produced and dissipated at a constant rate. Industrialization and increased energy demand on a global scale have created an environment where GHG are being produced at a much greater rate than they are cycled through the atmosphere (Gribbin, 1996). Agriculture has been identified as a large contributor to the surplus of atmospheric CH_4 (Harper et al., 1993). Of the agricultural CH_4 produced, a large portion can be attributed to the feeding of livestock animals (Harper et al., 1993). Ruminant animals are unique in anatomical design due to the placement of an anaerobic digestive environment both before and after an enzymatic stomach. Because of this arrangement, ruminants are capable of deriving energy from highly fibrous forages (Franzluebbers, 2007). This fermentative process also allows ruminants to acquire and digest protein generated from microbial organisms within the rumen.

It is commonly believed that production of CH_4 is due to confined feeding operations in food animal production settings. Although large concentrations of cattle can produce large amounts of CH_4, animals in this sector of beef production produce less methane than animals on pasture (Nkrumah et al., 2006). Although there are some levels of CH_4 production that can be attributed to livestock consuming concentrated diets, the majority of CH_4 produced from ruminants occurs via digestion of fibrous feedstuffs such as forages (Moss et al., 2000). The process of fermentation is oxidative under anaerobic conditions occurring via the Embden-Meyerhof-Parnas pathway (Moss et al., 2000). This generates the oxidation NADH to NAD^+

leaving behind H^+ molecules in the rumen microenvironment. The presence of H^+ in the rumen have negative effects on rumen microorganisms as it reduces the pH of the rumen. A competitive pathway for removal of H^+ molecules is the production of propionate. This VFA utilizes H^+ as opposed to acetate and butyrate pathways which produce H^+ and ultimately contribute to production of CH_4. Ruminal methanogens use free H^+ molecules as a way of eliminating this by-product of fermentation from the rumen environment (Iannotti et al., 1973), which is an important tool for maintaining a slightly acidic rumen pH. Removal of these occurs through the pairing of H^- molecules with CO_2 to form CH_4 and water (H_2O). Once CH_4 is generated, it is then released back into the environment via eructation (Russell, 2002).

Brassica species have been shown to be highly digestive forages that can reduce the production of methane in the rumen (Dillard et al., 2018). However, the mechanism of reducing methane during fermentation is not well understood. Multiple studies have been conducted to investigate the effects secondary of plant metabolites on digestibility and CH_4 production in brassicas. Glucosinolates (GSL) serve a protective role within brassicas. Glucosinolates create a bitter taste that discourages herbivory from multiple animals and insects (Sun, 2020). Dillard et al. (2019) investigated the digestibility of forage mixtures containing grasses and brassicas compared with grass-only samples in a continuous culture system. This study found that inclusion of brassicas had minimal effects of digestibility but decreased the production of CH_4 by 84%. The authors of this study conducted multiple regression analysis to determine if plant CWC or GSL were the causative agent of decreased CH_4 and found that NDF had the greatest effect on CH_4 production in this study. Other studies have found similar results. Sun et al. (2015) found that brassicas had greater digestibility and generated less CH_4 than grasses, when fed to sheep, due to the presence of GSL in brassicas. The authors discussed that GSL were responsible for reduced CH_4 based on results from previous studies that showed reduced CH_4 from brassicas when compared with legumes of similar quality (Sun et al., 2014). The mechanism that GSL reduced methane is still not well understood. Proposed mechanisms include that GSL could potentially alter rumen microbes responsible for producing CH_4 similar to condensed tannins found in certain legumes (Sun, 2020) and that GSL could alter animal endocrinology so that gut retention is reduced, and less time is available for CH_4 production (Barnett et al., 2012).

Further research is needed to determine the effects of grazing on specifically bred cover crop species and varieties. Investigation of grazing management strategies and animal performance of grazed cover crops systems are also needed. The subsequent chapters attempt to quantify optimal grazing management through use of different cattle removal dates. Determination of forage digestibility and VFA production throughout the growing season also provide necessary information to determine what optimal grazing of cover crops may be.

Chapter II: Grazing cover crops: Effects on animal and cover crop performance

2.1 Introduction

Cover crops were a traditional management tool in cropping enterprises until the industrial and technological revolutions of the 20th century (Franzluebbers, 2007). Emphasis on increased agricultural production gave way to a period intensive agriculture systems that are managed via synthetic fertilizers and chemical pest control. Environmental concerns in monoculture systems such as soil erosion and nutrient runoff have led to a revitalization of cover crops and renewed interest in their role in ecosystem sustainability. Cover crops provide many environmental benefits such as reducing erosion (Langdale et al., 1991), nutrient leaching and runoff (Li et al., 2006), inhibiting insect and weed encroachment (Creamer and Baldwin, 2000), and increasing soil fertility (Cavigelli and Thien, 2003). Although highly beneficial from an environmental standpoint, adoption of cover crops has been slow primarily due to the delayed economic return on their use.

Increases in population and urbanization in the developed world have led to increased awareness of the need for a sustainable food supply. Technological advancements have brought forth an age where people have more disposable income for food products (Ivanic and Martin, 2018). This has resulted in a greater dependency on large-scale food production among consumers (Franzluebbers, 2007; De Baets et al., 2011). The increase in demand for food and other agricultural products are likely to be paired with a decrease in land available for growing food crops and livestock. As land availability decreases, the need for increased production efficiency increases. Crop-livestock systems could potentially serve a dual role by producing agricultural products during times when crops are not growing while increasing opportunities for maintaining or enhancing the surrounding agroecosystem and producing a sustainable food supply with less land resources (Franzluebbers, 2007).

Integration of crop and livestock systems can be a valuable management strategy that allows for coupling of two complementary enterprises. Cover crops often use plant species that can be used as forage species. These forages are typically nutrient-dense, providing adequate CP and energy for all classes of cattle (NRC, 2016). Plant species that can be used as cool-season annual forage and for cover crop production include small grains (wheat (*Triticum aestivum*), oat (*Avena sativa*), and cereal rye (*Secale cereal*)), annual ryegrass (*Lolium multiflourm*), clovers (*Trifolium spp.*), and brassicas (*Brassica spp.*). These forages are often used for stocker cattle production in the Southeast. Multiple studies from the Southeast have demonstrated that grazing of cool-season annuals can be advantageous for stocker gains and total production per land unit (Beck et al., 2014; Mullenix et al., 2014; Marchant et al., 2019). Studies have reported that grazing of cover crops has minimal to no effect on soil quality parameters such as bulk density, water holding capacity, nitrogen (N) cycling, and soil organic matter (SOM) (Franzluebbers and Steudemann, 2008a; Tracy and Zhang, 2008) or subsequent cash crop yields (Balbinot Junior et al., 2011; Kelly et al., 2021). The introduction of grazing livestock to cover crops allows producers the opportunity to diversify their economic return, while still maintaining the environmental benefits that cover crops provide within the system.

The presence of cattle on cover crops provides ecosystem services to cropland through plant defoliation that would otherwise be conducted through various chemical applications. However, recommendations on proper grazing management of a multi-species cover crop are unclear. Although forages used in cover crop mixtures can serve as effective grazing crops, it is not well understood how specific plant species will respond to grazing pressure and subsequent potential beef production per hectare using these mixtures. Grazing management for traditional annual forage systems places emphasis on increased forage utilization throughout a grazing season. It is unknown if cover crops can withstand grazing pressure throughout an extended period or if they require early removal of cattle to allow for adequate regrowth in order to provide ecosystem services to the system for crop production. Further investigation is needed to determine if cool-season cover crops can be a viable grazing source for stocker cattle, while still maintaining their role in providing ecological stability. The objective of this study was to evaluate the forage production and animal performance of steers grazing cool-season annual cover crops with differing cattle removal dates.

2.2 Materials and Methods

2.2.1 Research Site

A 3-yr grazing experiment was conducted at the Wiregrass Research and Extension Center in Headland, Alabama (31.35°N lat., 85.34°W long.). The experiment was conducted under the approval of the Auburn University Institutional Animal Care and Use Committee (# 2018-3425). Twelve, 0.6-ha paddocks composed of Dothan fine sandy loam (Fine-loamy, kaolinitic, Plinthic Kandiudults) were used for this experiment. In 2018, prior to Year 1 (2019), paddocks were planted in annual peanut (*Arachis hypogaea* L.). The field was managed in a two-crop rotation of cotton (*Gossypium hirsutum* L.) and annual peanut. Cotton was established following Yr 1 and 3 (2021) and annual peanut following Yr 2 (2020).

2.2.2 Paddock Establishment and Fertilization

Paddocks were planted with a four-species cover-crop mixture each of the three years of the study. The cover crop mixture consisted of 'FL401' cereal rye (Melton Seed, Dade City, FL) 'Cosaque' oat (Petcher Seed, Fruitdale, AL), 'AU Sunrise' crimson clover (*Trifolium incarnatum;* Petcher seed, Fruitdale, AL), and 'T-raptor' brassica (*Brassica napus* × *B. rapa*; Southeast Agriseed, Rome, GA). Paddocks were seeded with a no-till drill (Great Plains Mfg., Salina, KS) into remaining crop residue from the previous season on October 29, 2018 in Year 1, November 4, 2019 in Year 2, and October 16, 2020 in Year 3. The species in the forage mixture were kept consistent year to year. Grazed paddocks were seeded with 40.9 kg pure live seed (PLS) /ha cereal rye, 40.9 kg PLS/ha oat, 13.6 kg PLS/ha crimson clover, and 2.7 kg PLS/ha brassica. Non-grazed pastures were seeded at 27.3 kg PLS/ha cereal rye, 27.3 kg PLS/ha oat, 13.6 kg PLS/ha crimson clover, and 2.7 kg PLS /ha brassica. Grazed paddocks were seeded at higher rates of cereal rye and oat as an effort to support grazing pressure from cattle. All paddocks were planted using a 19-cm row spacing. Grasses were planted to a depth of 2.5 cm while clover and brassica were planted to a depth of 1.25 cm. In each year, grazing paddocks were fertilized with 67 kg N/ha and control paddocks fertilized with 34 kg N/ha in the form of ammonium sulfate [$(NH_4)_2SO_4$] in December prior to grazing in January. Application of P and K occurred prior to planting of summer cash crops in the field according to soil-test recommendations provided by the Auburn University Soil Testing Laboratory (Auburn, AL) except for yr 3 when 54 kg/ha K was applied to all paddocks in the form of K_2O, respectively, on December 14, 2020, following harvest of peanuts.

2.2.3 Animal and Forage Management

Grazing paddock served as the experimental unit. Each paddock was randomly allocated to one of four cattle removal treatments: (1) no grazing (CON); (2) February removal (FEB); (3) March removal (MAR); or (4) April removal (APR). Each treatment was replicated three times resulting in 12, 0.62 ha paddocks. Angus crossbred steers were received and maintained on *ad libitum* bermudagrass (*Cynodon dactylon*) hay for 60 days prior to grazing. Before the experiment, animals were tagged for identification, dewormed with Cydectin pour-on dewormer (Boehringer Ingelheim, Ridgefield, CT), and implanted with a Ralgro implant (Merck Animal Health Intervet Inc., Madison, NJ). Steers had access to *ad libitum* commercial mineral mix (Mag Plus beef Mineral/salt, Southern States Cooperative Inc., Richmond, VA) and clean water. Three tester steers (7 mo in age; initial BW 266 ± 10 kg) were randomly allocated based on mean BW to grazing treatments in each of Year 1, 2, and 3 and allowed to graze once the mean forage biomass exceeded 1000 kg/ha DM in all paddocks (Marchant et al., 2019). Tester steers were used for calculation of initial BW, final BW, and ADG. Steers were weighed prior to initiation of grazing and again following removal from the paddock at the end of the designated grazing period. Average daily gain was measured by subtracting the final weight by the initial weight and dividing by the number of days on pasture. Grazing was initiated in January of each year (Table 1). Stocking density adjustments were made every 2 weeks according to mean forage biomass and steer BW (Mullenix et al., 2014). In all three years, a target forage allowance was maintained using the put-and-take method (Sollenberger and Burns, 2001). A forage allowance of 1 kg DM/1 kg BW (Marchant et al., 2019) was maintained during the grazing season. Additional BW gain from put-and-take steers was measured similarly to and combined with tester steers to determine total BW gain per hectare, stocking density, forage allowance, and grazing days per hectare for each treatment (Beck et al., 2014). Cattle were removed from paddocks based on their treatment designation date or when forage availability fell below 880 kg DM/ha.

Table 1. Grazing initiation and termination dates for cover crops under different grazing regimes

	Treatment[1]			
Year	**CON**	**FEB**	**MAR**	**APR**
Spring 2019				
Grazing initiation	-	January 11	January 11	January 11
Grazing termination	-	February 14	March 1	April 15
Length of season (d)	-	34	49	94
Spring 2020				
Grazing initiation	-	January 13	January 13	January 13
Grazing termination	-	February 12	March 9	April 10
Length of season (d)	-	30	56	88
Spring 2021				
Grazing initiation	-	January 4	January 4	January 4
Grazing termination	-	February 15	March 15	March 15
Length of season (d)	-	42	70	70

[1] CON = Control; FEB= February cattle removal; MAR = March removal of cattle; APR = April removal of cattle

2.2.4 Forage Sampling and Laboratory Analysis

Forages were sampled immediately prior to experiment initiation and every two weeks thereafter. Four random samples were collected from each paddock to determine forage biomass and nutritive value. Two additional samples were taken from each paddock to determine botanical composition. Samples were clipped to approximately 5 cm within a 0.1-m^2 quadrat, placed in cloth bags, and transported to the Auburn University Ruminant Nutrition Laboratory (Auburn, AL). Forage biomass samples were dried at 60°C in a forced-air oven for 48 h or until dry and then air equilibrated and weighed. Samples collected for analysis of botanical composition were separated upon arrival into three groups: (1) grass; (2) clover; or (3) brassica. Each group was then placed in paper bags and dried at 60°C in a forced-air oven for 48 h or until dry and then air equilibrated and weighed. Weights from each botanical composition group were then combined and used to calculate percent botanical composition of each forage group. Forage allowance (FA) was calculated using Equation 1.

Eq. 1

$$FA = Available\ Forage\ \left(kg\,\frac{DM}{ha}\right) \div Total\ BW\ per\ paddock\ \left(\frac{kg}{paddock}\right)$$

Dried forage samples were ground in a Wiley Mill (Thomas Scientific, Swedesboro, NJ) to pass a 2-mm screen. Crude protein and DM were analyzed using procedures of AOAC International (1995). Fiber fractions (NDF, ADF, and ADL) were determined using methodology of Van Soest et al. (1994).

2.2.5 Statistical Analysis

Data were analyzed as a completely randomized design with paddock serving as the experimental unit. All data were analyzed using the PROC MIXED procedure of SAS version

9.4 (SAS Institute Inc., Cary, NC). Treatment served as the main effect for forage biomass, nutritive value, ADG, total BW (body weight) gain per hectare, initial BW, final BW, forage allowance, and stocking density. Treatment, species, and treatment × species interactions were the main effects for analysis of percent botanical composition. Year was considered a random effect, and sampling date was considered a repeated measure. Control paddocks were not included in analysis of forage allowance, grazing days, ADG, total BW gain per hectare, initial BW, final BW, or stocking density. Pearson correlation coefficients were determined to relate forage metrics to ADG using PROC CORR of SAS. A stepwise regression was conducted using PROC REG of SAS to predict statistical associations between forage characteristics and dependent variables. Treatment means were separated using the PDIFF option of LSMEANS when protected by F-test at $\alpha = 0.05$.

2.3 Results

2.3.1 Weather conditions

Total monthly precipitation and mean temperatures were collected from October through April of each year of the study. In Year 1 (2018 – 2019), temperature was on par with the 30-year mean in all months with the exception of November and February (Figure 1). The November 2018 mean temperature was 20% below the 30-year average, whereas February temperatures were 20% greater than the 30-year mean. Rainfall in the fall of 2018 (September – December) was 53% greater than the 30-year mean, but it was 50% less than the spring mean in all years (Figure 2). In Year 2, temperatures were above the 30-year mean in all months except November, which was 10% lower than the average. Rainfall in Year 2 was sporadic; December, February, and April precipitation were 44%, 34%, and 37% greater than the 30-year mean, respectively, while November, January, and March were 42%, 72%, and 73% below the average, respectively. In Year 3, temperatures were slightly above or on par with the 30-year mean with the exception of February, when temperatures were 55% below the average. Rainfall in Year 3 was 52% below the 30-yr mean in the fall, but 9% above the 30-year mean in the spring.

2.3.2 Seasonal forage biomass and composition

Seasonal forage biomass was 40, 54, and 52% greater in CON paddocks than FEB, MAR, and APR, respectively ($P = 0.001$) (Table 2). No difference was observed among grazing treatments across the three-year evaluation, however ($P = 0.52$). Furthermore, no differences were detected among grazing treatments for forage allowance, grazing days per hectare, or stocking density ($P = 0.59$, 0.52, 0.11, respectively). Percent botanical composition of grasses was 75% greater than clovers ($P < 0.0001$) and 86% greater than brassicas ($P < 0.0001$), whereas percent clovers was 45% greater than percent brassicas during the length of the grazing season

($P < 0.0001$) (Table 3). No differences were present for species × treatment interactions for species botanical composition ($P = 0.19$).

2.3.3 Forage nutritive value and animal performance

Crude protein concentration in MAR paddocks was 13% greater than CON paddocks ($P = 0.02$) (Table 4). No difference was detected among treatments for NDF ($P = 0.98$) or ADF ($P = 0.95$), but ADL concentration of MAR and APR paddocks were 33% and 27% greater than CON paddocks, respectively ($P < 0.05$).

No differences were detected among treatments for initial BW, ADG, or BW gain per hectare ($P = 0.99$, 0.12, and 0.85, respectively) but differences were observed for final body weight (Table 5). Final BW for cattle on APR paddocks was 9% greater than those grazing MAR paddocks ($P = 0.0004$) and 15% greater than those in FEB paddocks ($P < 0.0001$). The final BW of cattle from MAR paddocks were 6% greater than those grazing FEB paddocks ($P = 0.03$).

Comparison of forage metrics to ADG via Pearson correlation coefficient analysis demonstrated that ADG was negatively correlated with NDF, ADF, and forage allowance ($P = 0.0001$, 0.004, and 0.03) (Table 6). Multiple stepwise regression illustrated that NDF had a negative causative relationship with ADG (-0.06 ± 0.01; Partial $r^2 = 0.48$; $P < 0.0001$). Grazing days, forage allowance, stocking density, and concentration of ADF, ADL, and CP did not meet the significance criteria necessary to enter the model ($P = 0.15$).

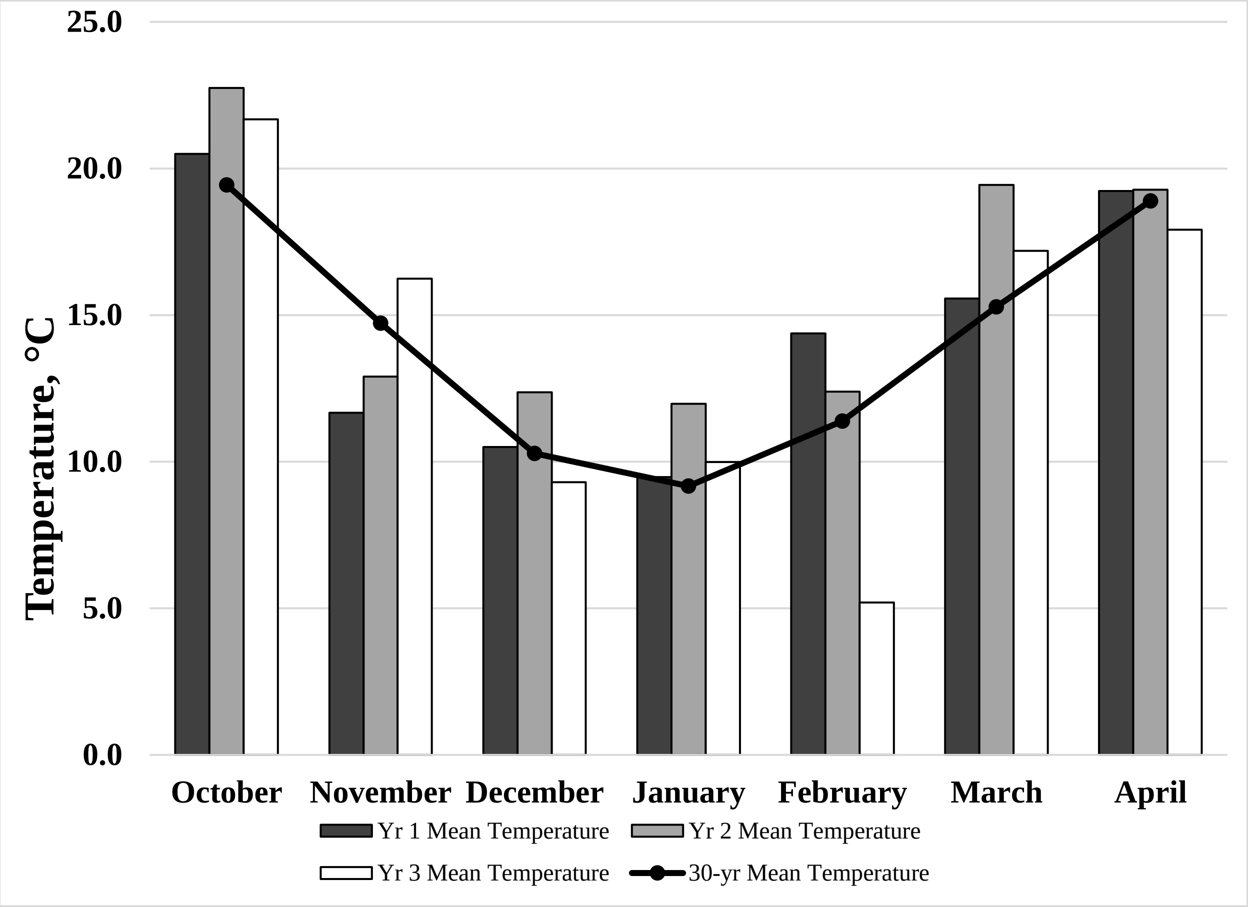

Figure 1. Monthly and 30-year mean temperatures for October through April at the Wiregrass Research and Extension Center, Headland, AL; Year 1, 2018 – 2019; Year 2, 2019 – 2020; Year 3, 2020 – 2021.

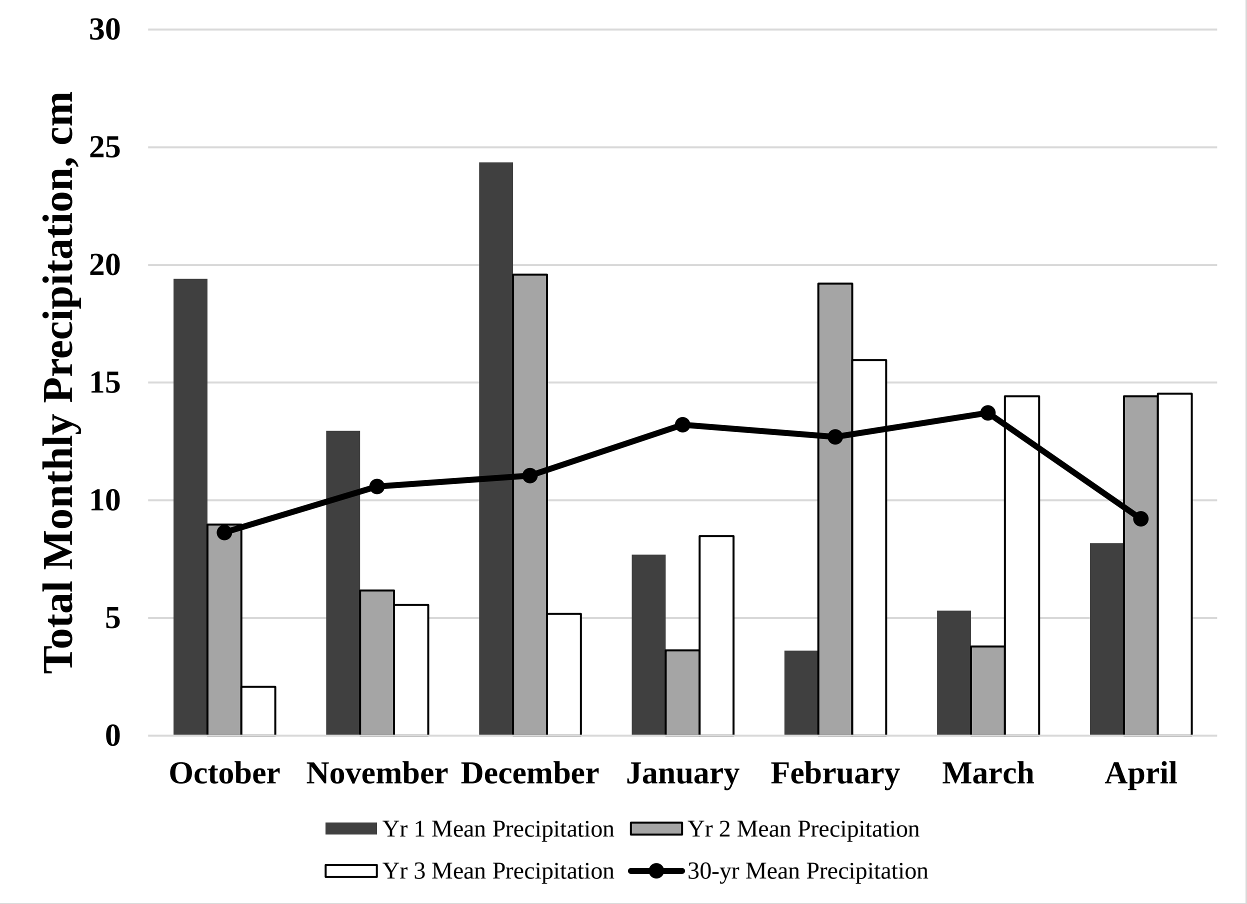

Figure 2. Total monthly precipitation and 30-year mean precipitation for October through April at Wiregrass Research and Extension Center, Headland, AL; Year 1, 2018 – 2019; Year 2, 2019 – 2020; Year 3, 2020 – 2021.

Table 2. Mean forage biomass, forage allowance, grazing days per hectare, and stocking density of cover crops consisting of cereal rye, oat, crimson clover, and brassica under different grazing regimes.

Item	**CON[1]**	**FEB**	**MAR**	**APR**	**Mean**	**SE**
Forage biomass, kg DM/ha	3912^{a}	2397^{b}	1908^{b}	2126^{b}	2585	204.0
Forage allowance, kg DM/kg of BW	-	0.86	0.84	0.76	0.82	0.06
Grazing days per hectare, d/ha[2]	-	369	490	622	493	87.0
Stocking density, steers/ha	-	5.8	5.6	4.6	5.4	0.62

[1] CON = Control; FEB= February cattle removal; MAR= March removal of cattle; APR = April removal of cattle.

[2] Calculated as stocking density (steers/ha) × length of grazing season (d).

^{abc}Within a row, values without a common superscript differ ($P < 0.05$).

Table 3. Percent botanical composition of grasses, clover, and brassicas in cover consisting of cereal rye, oat, crimson clover, and brassica under different grazing regimes.

Item	**CON**[1]	**FEB**	**MARCH**	**APRIL**	**Mean**	**SE**
Brassica, %	9	10	13	10	11^{c}	0.02
Clover, %	15	14	13	12	13^{b}	0.02
Grass, %	76	76	74	78	76^{a}	0.02

[1] CON = Control; FEB= February cattle removal; MAR = March removal of cattle; APR = April removal of cattle.

[abc] Within a column, values without a common superscript differ $P < 0.05$.

Table 4. Nutritive value of cover crops consisting of cereal rye, oat, crimson clover, and brassica under different grazing regimes.

Item[2]	CON[1]	FEB	MAR	APR	Mean	SE
CP, %	11.8^{b}	12.3^{ab}	13.4^{a}	12.6^{ab}	12.5	0.48
NDF, %	52.6	51.8	53.0	52.5	52.5	1.40
ADF, %	31.2	30.2	31.2	30.7	30.8	0.83
ADL, %	4.4^{b}	5.4^{ab}	6.5^{a}	6.0^{a}	5.6	0.46

[1] CON = Control; FEB= February cattle removal; MAR= March removal of cattle; APR = April removal of cattle.

[2] CP = crude protein; NDF = neutral detergent fiber; ADF = acid detergent fiber; ADL = acid detergent lignin.

^{abc}Within a row, values without a common superscript differ (P < 0.05).

Table 5. Initial body weight (BW), final body weight, average daily gain (ADG), and total body weight gain per area of steers grazing cover crops consisting of cereal rye, oat, crimson clover, and brassica under different grazing regimes.

Item	CON[1]	FEB	MAR	APR	Mean	SE
Initial BW, kg	-	266	266	266	266	10.0
Final BW, kg	-	304^c	323^b	355^a	327	6.0
ADG, kg	-	1.1	1.1	1.3	1.2	0.07
BW gain/ha, kg	-	388	466	416	424	90.0

[1] CON = Control; FEB= February cattle removal; MAR = March removal of cattle; APR = April removal of cattle.

^{abc}Within a row, values without a common superscript differ ($P < 0.05$).

Table 6. Correlation coefficients[1] (r) between forage characteristics and average daily gain (kg/d) by beef steers grazing cover crops consisting of cereal rye, oat, crimson clover, and brassica under different grazing regimes

Item[2]	**r**	***P*-value**
CP	-0.23	0.23
NDF	-0.69	< 0.01
ADF	-0.54	< 0.01
ADL	-0.30	0.12
FA	-0.41	0.03
SD	-0.06	0.77

[1] Correlation values were derived from data collected on a bi-weekly basis when steers were grazing pasture.

[2] CP= crude protein (%); NDF=neutral detergent fiber (%); ADF= acid detergent fiber (%); ADL= acid detergent lignin (%); FA= forage dry matter allowance (kg of dry matter/kg of steer BW); SD= stocking density (steers/ha).

2.4 Discussion

2.4.1 Seasonal forage biomass and botanical composition

Differences in forage biomass between ungrazed and grazed treatments confims that presence of grazing cattle will reduce total biomass accumulation regardless of cattle removal date. Franzluebbers and Steudemann (2014) found similar results when comparing grazed and ungrazed cover crops under different tillage treatments. Although final biomass can be used as a suitable indicator of ground cover at the end of the growing season, it does not account for the biomass fluctuations within the crop that might be present throughout the season. Ungrazed pastures will gradually increase in biomass production until plants reach maturity. Grazed pastures will increase and decrease depending on the interactions among forage allowance, weather, and plant physiological state. The lack of difference in forage biomass among grazing treatments (i.e., FEB, MAR and APR) in the current study can be attributed to no differences in forage allowance, grazing days/ha, and stocking density that result from put-and-take grazing management to biomass shortages throughout the year. Cattle were temporarily removed in all three years due to biomass shortage and permanently removed in Yr 3 in APR paddocks prior to their prescribed removal date (Table 1). Marchant et al. (2019) reported stocking density (2.94 steers/ha) and forage allowance (0.89 kg DM/kg steer BW) generating a mean value of 375 grazing days, similar to the current study, for crops containing cool-season annual grasses such as wheat (*Triticum aestivum*), triticale (×*Tritcosecale*), and annual ryegrass (*Lolium multiflorum*) illustrating that the cover crop mixture used is capable of generating a comparable number of grazing days per ha.

Stocking density for the current study was 23% lower than data reported in Mullenix et al. (2014) which is likely due to the absence of annual ryegrass in the current study. Presence of annual ryegrass has been shown to allow for greater stocking later in the spring due to the high amounts of biomass produced during this season. Use of annual ryegrass could potentially increase grazing days, stocking density, and forage allowance of cover-crops because of its contribution to increased forage biomass production in the late spring. However, the presence of annual ryegrass in a cropping system could be detrimental because of the tendency of this forage to persist and act as an invasive weed in croplands (Matthews et al., 1996). The inability to include annual ryegrass creates a cover crop mixture that is earlier maturing with little potential for forage biomass production late in the spring, which also increases the difficulty in managing biomass availability early in the growing season to sustain soil protection throughout the season. Removal of grazing animals prior to cover crop termination would allow for increased biomass accumulation that could provide adequate soil protection. This premise led to the treatment design of the current study so that determination of how much regrowth time is needed could be determined. The lack of above-ground plant material as a result of grazing creates a deficit in physical plant materials necessary to prevent soil erosion and nutrient runoff. A lack of statistical differences in grazing days per hectare limit the conclusions that can be drawn from allowing a plant regrowth period following grazing in the current study, however.

A target forage allowance of 1 kg DM/1 kg BW was established at the beginning of the experiment. This target establishes a stocking strategy that enables increased forage utilization in an attempt to increase total BW gain per hectare. The actual mean forage allowance for the current study was 18% lower than the prescribed target allowance. The target forage allowance used in the current study has been shown to be effective in conventional stocker cattle grazing systems that focus on forage utilization levels as great as 80% (Marchant et al., 2019). Data from the current study indicate that this stocking and grazing strategy may not translate well to grazed cover crop systems, especially with the absence of annual ryegrass in the cover crop mixture. Management of ungrazed cover crops and cool-season annual grazing systems have different goals that require unique management. Forage species chosen for stocker cattle grazing have growth patterns that extend grazing season length while targeting maximum performance per hectare. Forage species used in cover crop mixtures are typically chosen based solely on their ability to serve as a soil ground cover as opposed to a grazing crop, as was the case in this study. As a result, early maturing forage species and varieties such as FL401 cereal rye were included in the mixture. FL401 cereal rye and AU Sunrise crimson clover are known to accumulate large amounts of biomass early in the season but are not as productive later in the spring (Mosjidis et al. 2000; Dubeux et al., 2016). Planisch et al. (2021) reported that moderate stocking of cereal rye cover crops with a 15 cm target residual height resulted in the greatest ADG and BW gain per hectare, while still maintaining forage availability. Lower residual heights resulting from either heavier stocking densities or increased grazing days create a deficiency in animal DM intake that inhibits animal gains and reduces aboveground biomass, thus reducing the effectiveness of the cover crop. Greater forage residual heights would allow for increased aboveground biomass that is necessary for cover crops to provide benefits to the cropping system such as weed inhibition and increased soil organic matter (Altieri, 2009). However, excess forage biomass will result in more mature forages that have increased proportions of lignin and insoluble fiber and decreased proportions of available energy, CP, and digestibility (Chaves et al., 2006). The result is lower-quality forage and decreased ADG of grazing steers. While forage biomass will be increased, lower forage quality paired with fewer animals per unit land area will likely result in less BW gain per hectare and economic return from animal integration within the system. This measurement of animal performance is the most economically relevant as it quantifies animal production per unit land area as opposed to individual animal performance. The management of moderate stocking rates through measuring residual forage heights (15 – 20 cm) would result in more consistent animal gains and forage production throughout the grazing season (Plainisch et al., 2021).

Forage species and varieties used in the current study were chosen specifically because of their previous characterization as early-maturing. Specifically, FL401 cereal rye has been shown to be useful in mixtures for early spring grazing in northern Florida (Dubeux et al., 2016). The authors concluded that while this variety of cereal rye was useful for early-season grazing, it decreased in yield and nutritive value during mid and late-season. Studies using AU Sunrise crimson clover have found similar results. Mosjidis et al. (2000) observed that AU Sunrise flowered 5 to 18 days sooner than the next earliest maturing variety of crimson clover. Brassicas are generally known for their early-season growth (Dillard et al., 2018). Research in Georgia reported that T-raptor was early maturing and less productive when planted in late fall (Denman et al., 2021). Paddocks in the current study were planted no earlier than October 16th due to the harvesting of the previous cash crop. Harvesting of peanuts traditionally occurs up to a month earlier than cotton. Planting immediately following peanut harvest will exacerbate problems associated with early maturing forage stands. Earlier initiation of grazing or selection for later maturing forage species and/or varieties may be necessary to increase forage allowance and BW gain per hectare. Forage mixtures in the current study provided ample grazing early in the season (1908 – 2397 kg DM/ha), but often required destocking of animals periodically throughout the season beginning as early as February as a result of aboveground forage biomass falling below 1,000 kg DM/ha. Other studies have shown lessor winter stocking densities and greater spring stocking densities (Beck et al., 2014; Marchant et al., 2019). These studies included annual ryegrass which likely is responsible for the greater late-season forage growth compared with the current study. Future research with forage mixtures should be selected so that as animal weights and DM intake increases with growing beef calves, the forage biomass growth increases accordingly. Although steers in the current study were able to graze extra pasture of the same forage mixture to maintain a consistent diet throughout the season, this specific forage mixture did not sustain continuous stocking throughout a spring grazing season.

Lack of differences in botanical composition among treatments in the current study indicate that presence of grazing and length of grazing have no effect on persistence of any plant group throughout the season. Percentages of each plant within the sward are similar to the rate at which they were seeded. Grasses (cereal rye and oat) comprised 83% of the total mixture in terms of total kg seed at planting, and grasses made up 74% of the forage stand during the grazing season. Grasses remained dominant throughout the growing season. Crimson clover seed accounted for 14% of the total mixture at planting and 14% of the forage stand during the grazing season. Majority of crimson clover harvested emerged in March and April, however. Lastly, T-raptor made up only 3% of the seed mixture and accounted for 10% of the total forage during the grazing season. Time of emergence was similar to grasses, but prevalence within the forage mixture decreased as the season progressed. Differences in total mean composition indicate that grasses will be the predominate forage in mixtures. Brassicas have the ability to provide early-season biomass during the fall but will decrease in production during winter due to their lack of cold tolerance (Dillard et al., 2018). Crimson clover is opposite to the brassica species in its growth pattern having the greatest impact later in the grazing season.

2.4.2 Forage nutritive value and animal performance

Although differences were detected between CON and APRIL for CP and between CON and MAR for acid detergent lignin (ADL) concentration, nutritive value of cover crops was similar among treatments. Forage nutritive value of paddocks grazed in the current study are lower than those found in similar studies. Villalobos and Brummer (2017) reported that mixtures containing wheat, crimson clover, and brassica had 4% greater CP and 30% lesser NDF than the current study. Mullenix et al. (2014) found that monoculture stands of triticale (×*Triticosecale*) and wheat exhibited similar NDF and ADF values, while CP was 5% greater in triticale and 4% greater in wheat than the forage mixtures of the current study. Lignin in the current study was approximately 4% greater than data reported in Mullenix et al. (2014). A lack of difference among treatments can be attributed to increased maturity of cereal rye in all paddocks prior to initiation of grazing in January of each year. Similarity in nutritive value among treatments paired with poor biomass regrowth indicate that plants within the mixture may have already initiated maturation and reproduction (Chaves et al., 2006). Cereal rye in all three years of the study reached the boot stage of production prior to initiation of grazing in January. As a proportion of total forage biomass, cereal rye dominated forage stands in all three years of the study throughout the grazing season. Because aboveground biomass accumulation of cereal rye was greatly reduced later in the growing season, the dominance of cereal rye in the forage stand throughout the entire growing season was likely the result of animal selection. Although the forages in the current study were less than in other similar studies, they still fall within the TDN (> 60%) and CP (> 10.2%) ranges necessary to generate satisfactory BW gain in growing beef animals (NRC, 2016). Replacing early maturing forages with later maturing contemporaries

,which mature in March or April as opposed to January or February, could result in more desirable nutritive value and greater forage biomass.

Results for steer ADG were similar to those reported by Dubeux et al. (2016). These authors grazed mixtures of various small grains including FL401 cereal rye in combination with annual ryegrass in North Florida. Measures of BW gain per ha were greater than in the current study, but a longer grazing season and the inclusion of annual ryegrass could play a role in these differences. Initiation of grazing in Dubeux et al. (2016) began approximately 14 – 21 d earlier than in the current study which allowed animals more time on pasture and would result in further BW gains. Dubeux et al. found that as annual ryegrass increased in proportion within the mixture, the BW gain per hectare increased as well. Sampling periods within the study where small grains were dominant within the mixture exhibited similar BW gain per ha as in the current study. Mean ADG for the current study was slightly greater than ADG in Beck et al. (2014), although spring ADG values were greater than those reported in the current study. Inclusion of winter ADG results in values that are approximately 33% less than those found in the current study. This approach better matches the design of the current trial, but inclusion of brassicas and crimson clover must be considered when comparing current results with studies grazing forage stands consisting of grass monocultures.

Pearson correlation coefficient analysis revealed that both forage concentration NDF and allowance were negatively correlated with steer ADG. Multiple stepwise regression indicated that NDF concentration was the only forage characteristic that had affected ADG. This indicates that forage concentration NDF accounted for 48% of the variability in ADG. Mullenix et al. (2014) conducted similar analyses and found that ADF had a negative causative relationship with ADG. These data indicate that fiber fractions within forages can impact the performance of individual steers. Fiber fractions are related to forage energy concentration and availability for beef animals (NRC, 2016). As plants become mature, the proportion of cell wall fiber increases, therefore decreasing available energy. This should be considered when selecting forages to be included in cover crop mixtures. Although early-maturing forages provide biomass quickly for soil protection purposes, the usefulness of these forages as a grazing crop decreases quickly as plants mature.

Lack of differences in BW gain per ha among treatments in the current study indicates that no additional advantages are present when steers are allowed to remain on pasture for extended periods of time with this specific cover crop mixture. Effects are significant in tester animals' final BW, indicating that greater time on pasture results in greater total gain per animal. Periods of reduced stocking or destocking later in the grazing season could have affected BW gain per ha for MAR and APR paddocks to a point that any potential differences could have been nullified due to time off pasture. The inability to have increased stocking throughout an entire grazing season could limit the usefulness of extended grazing within this system. Decreasing stocking density through greater forage allowance could potentially mitigate losses in gain due to time off pasture. Alternatively, inclusion of annual ryegrass could increase stocking density and animal gains compared with the current system. Although there is some concern of annual ryegrass acting as an invasive weed, chemical termination of plants and warm-season weather will greatly reduce the chances of encroachment occurring. Termination of annual ryegrass prior to plants reaching the reproductive phase or use of tetraploid varieties is necessary to mitigate instances of volunteer stands in following years, however. Although extended grazing of cover crops in the current study shows no detriment to the overall production of forage biomass, there are no advantages in stocker cattle performance following extended grazing of cover crops.

2.5 Conclusions

In order to balance forage production and cattle performance in grazed cover crop systems, straightforward operational goals must be established. Data from the current study indicate that grazing of traditional cover crop mixtures cannot sustain grazing for extended periods of time using traditional stocking methods from previously conducted stocker cattle grazing studies. Grazing of cover crops can potentially provide additional winter grazing opportunities that otherwise would not be present. Other grazing management strategies should be explored, however. Franzluebbers and Steuddemann (2014) and Planisch et al. (2021) grazed cover crops to specific residual heights with cows and stocker cattle as opposed to prescribed removal dates. This method of stocking and removal allows for graziers to build flexibility into their grazing programs. Grazing to a specific residual height may not be as conducive for stocker producers whose goal is to increase animal performance through increased forage utilization. Using target residual heights could however be an effective strategy for managing stocking and removal of cows on winter grazing.

Current data and previous research indicate that cover crops are useful as a potential grazing source for short periods of time. Inclusion of different forage species and varieties could potentially extend grazing, but the benefits of different cover crop mixtures on soil and cash crop productivity must be considered as well. Further research is needed to determine what method of forage utilization is most efficient for production of cattle without negatively influencing the primary agronomic purpose of cover crops.

Chapter 3: *In vitro* digestibility of cover crops throughout the growing season

3.1 Introduction

Cover crops have become a revitalized management tool for cash-crop producers throughout the Southeast (Franzluebbers, 2007). In the 20th century, food production shifted from subsistence farming to industrialized monoculture cropping systems that were intensively managed via annual tillage, synthetic fertilizers, and chemical weed control (Franzluebbers, 2007). Monoculture cropping proved to be effective in obtaining high yields in cash crops in the short term, but crop production under this system generated multiple environmental hazards as a result of soil erosion, nutrient runoff, and herbicide resistant weeds, ultimately reducing the cash crop yield (Franzluebbers, 2007). Cover crops are an effective tool for mitigating environmental risks while maintaining crop production (Kelly et al., 2021). Their ability to reduce erosion (Langdale et al., 1990), nutrient runoff and leaching (Li et al., 2006), mitigate insect and weed encroachment (Creamer and Baldwin, 2000), and increase soil fertility (Cavigelli and Thien, 2003) make cover crops a valuable management tool. As beneficial as cover crops have proven to be from an ecosystem perspective, the adoption of this practice has been delayed due to its lack of immediate economic return.

Integrated crop-livestock systems have become a more commonly used practice to increase land use efficiency during cash crop off-seasons (Franzluebbers, 2007). The incorporation of grazing livestock such as cattle onto cropland can provide many ecosystem services that would otherwise be provided via synthetic products such as chemical fertilizer. Grazing of cattle on cover crops has been shown to have minimal effects on soil health (Tracy and Zhang, 2008) or cash crop performance (Balbinot Junior et al., 2011). However, the effectiveness of cover crop forage species as a grazing crop for cattle in terms of animal performance, stocking rate, and grazing season length to fully optimize both animal and crop perspectives is not fully established.

Cool-season cover crops often comprise annual forages that can serve as high quality grazing crops such as small grains, clovers, and brassicas. Multiple studies have been conducted to assess the use of various cool-season annual forages as grazing crops for growing stocker cattle in the Southeast (Beck et al., 2014; Mullenix et al., 2014; Marchant et al., 2019). Cool-season annuals can be effective grazing crops for stocker cattle, but it is unknown how suitable cool-season annual varieties commonly used for cover crop production will perform as grazing crops. Forage species used in cover crops are bred to mature early and produce biomass quickly as opposed to sustained production throughout the growing season (Mosjidis et al., 2000; Dubeux et al., 2016). This is an effective method for soil health purposes, but information on how maturity patterns of cover crops affect forage digestibility, rumen VFA production, and cattle GHG production are not reported in the literature.

Research has found that as forage maturity increases, the total digestibility decreases, but the corresponding ruminal VFA production is unaffected (Weaver et al., 1978; Chaves et al., 2006; Ribeiro Jr. et al., 2014). Digestibility could be reduced more rapidly as the growing season progresses and plants enter the reproductive stage of growth. This creates a scenario where animal performance will decrease and CH_4 production will increase. These changes in ruminal fermentation create both economic and environmental concerns associated with grazing cattle through altering time on pasture needed to achieve animal performance goals. Removal of cattle from cool-season annual cover crops is currently based upon forage metrics such as forage biomass residual. Determination of potential digestive kinetics could provide more information on when cattle should be removed from cover crops based on cattle digestive parameters. The objective of this study was to determine how harvest date of a cool-season annual cover crop mixtures influenced total forage digestibility, rumen VFA, and CH_4 production *in vitro*.

3.2 Materials and Methods

3.2.1 Research Site and Forage Management

Cover crop mixtures containing ‘FL401’ cereal rye (*Secale cereal*) (Melton Seed, Dade City, FL) ‘Cosaque’ oat, (*Avena sativa*) (Petcher Seed, Fruitdale, AL) ‘AU Sunrise’ crimson clover (*Trifolium incarnatum*) (Petcher seed, Fruitdale, AL), and ‘T-raptor’ brassica (*Brassica napus* × *B. rapa*) (Southeast Agriseed, Rome, GA) were planted at the Wiregrass Research and Extension Center in Headland, AL. Seeds were planted into crop residue of a crop rotation of cotton (*Gossypium hirsutum* L.) and annual peanut (*Arachis hypogaea* L.) using a no-till drill (Great Plains Mfg., Salina, KS) for three years. Planting of cover crops occurred November 6, 2018 in Year 1, November 4, 2019 in Year 2, and November 5, 2020 in Year 3. In all three years, planting date was determined according to harvest date of the preceding cash crop. Forage mixtures were consistent year to year with paddocks being seeded with 40.9 kg/ha ‘FL401’ cereal rye, 40.9 kg/ha ‘Cosaque’ oat, 13.6 kg/ha ‘AU Sunrise’ crimson clover, and 2.7 kg/ha ‘T-raptor’ brassica. Paddocks were fertilized with 54 kg/ha of N in the form of ammonium sulfate $[(NH_4)_2SO_4]$ in December of every year prior to grazing iniation in January. Application of P and K occurred prior to planting of summer cash crops in the field according to soil-test recommendations provided by the Auburn University Soil Testing Laboratory except for Year 3 when 54 kg/ha K was applied to all paddocks in the form of K_2O, respectively, on December 14, 2020 following harvest of peanuts.

Paddocks were grazed with steers beginning on January 11, 2019, January 2, 2020, and January 2, 2021 in Years 1,2, and 3, respectively. Grazing was terminated on April 15, 2019, April, 10, 2020, and March, 15, 2021 in Years 1, 2, and 3, respectively. Paddocks were stocked with steers to maintain a target forage allowance of 1 kg BW/1 kg forage DM to prevent overgrazing. Forage samples were collected monthly from each paddock. Samples were collected within the first week of every month. Samples were clipped to approximately 5 cm within a 0.1-m^2 quadrat, placed in cloth bags, and transported to the Auburn University Ruminant Nutrition Laboratory (Auburn, AL). Samples were dried for 48 h at 60°C, air equilibrated, and weighed. Dried forage samples were ground in a Wiley mill (Thomas Scientific, Swedesboro, NJ) to pass a 2-mm screen. Crude protein and dry matter (DM) concentrations were analyzed using procedures of AOAC International (1995). Fiber fractions including neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) were determined using methodology of Van Soest et al. (1994).

3.2.2 Fermentation Design and Operation

The experiment was a generalized complete block design with forage harvest date serving as the treatment and digestion period serving as the block. Treatments were (1) January (JA); (2) February (FE); (3) March (MA); or (4) April (AP) harvest dates. Forage samples from grazed paddocks were fermented for either 2, 4, 8, 24, or 48 hours. Batch culture fermentation was conducted at the Auburn University Ruminant Nutrition laboratory (Auburn, AL). A 0.5-g forage sample was weighed into an ANKOM 2000 fiber bag (Ankom Technology Corporation, Fairport, NY). Forage *in vitro* DM digestibility (IVDMD), NDF digestibility (NDFD), and ADF digestibility (ADFD) were conducted using methodology of Tilley and Terry (1963) with a mineral buffer modification according to Van Soest (1994).

Two ruminanlly fistulated, non-pregnant, non-lactating *Bos taurus* heifers (363 ± 23 kg; 15 mo of age) were used for ruminal fluid and digesta collections in accordance with the Auburn University Animal Care and Use guidelines (#2021-3987). Donor heifers were group housed and fed a diet of 'Coastal' bermudagrass (*Cynodon dactylon*) hay and supplemented with a textured

13% CP feed supplement consisting of grain and roughage by-products, and calcium carbonate at 1% BW DM in a feed bunk at the Auburn University Beef Teaching Unit. Heifers were acclimated to diet for 14 days prior to first rumen fluid and digesta collection. For each heifer, approximately 2 h after morning feeding, 2 L of rumen fluid was collected from four different regions of the rumen with a hand pump into a prewarmed container and maintained at 39 °C. Samples were transported back to the laboratory and strained through four layers of cheesecloth within 30 min of collection. Ten mL of strained rumen fluid was then added to mineral buffer solution at a 1:4 ratio in 125 mL Erlenmeyer flasks. Forage sample bags were placed in each flask before being flushed with CO_2 and sealed with a rubber stopper. Sealed flasks were then placed in a shaking water bath at 39 °C until reaching their prescribed removal time. Following removal, samples were rinsed with deionized water before being frozen at -20 °C. Samples remained frozen until they were processed for nutritive value analysis where they were thawed immediately prior to NDF and ADF determination.

3.3.3 Methane and VFA Collection and Measurements

Methane (CH_4), hydrogen (H^+), and VFA samples were collected at 48 h *in vitro*. Headspace gas was collected using a 20 mL glass syringe and a 22.5-gauge needle. Gas samples were drawn from each sealed flask using a gas-tight syringe and injected into a CO_2 flushed and sealed Wheaton bottle (DWK Life Sciences, Millville, NJ). Samples were kept refrigerated at 3 °C until measurement occurred. Methane and H^+ were analyzed by gas chromatography using a GOW-MAC thermal conductivity series 580 gas chromatograph (GOW-MAC Instrument Co., Bethlehem, PA) equipped with a HayeSep Q column (60 °C and 25 mL/min of argon carrier gas; Valco Instruments Co. Inc., Houston, TX). Following gas collection, rubber stoppers were removed, and 1 mL liquid was collected. Rumen fluid was acidified using 20 µL 2% (vol/vol) sulfuric acid prior to determination of VFA. Acetate (A), Propionate (P), Butyrate (B), Valerate, Isobutyrate, Isovalerate, A:P and A+B:P+V were measured. Volatile fatty acids were analyzed by gas-liquid chromatography using the method described by Akins et al. (2009).

3.3.4 Statistical analysis

All data were analyzed using the PROC GLIMMIX procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC). Treatment served as the main effect for VFA, CH_4, and H^+ and block served as a random effect. Treatment, digestion time, and treatment × digestion time interactions served as the main effects for analysis of IVDMD, NDFD, and ADFD, while block served as a random effect. Treatment means were separated using the PDIFF option of LSMEANS when protected by *F*-test at $\alpha = 0.05$.

3.3 Results

3.3.1 Forage Digestibility

Statistical analysis indicated that treatment × time interactions were observed for various nutritive value parameters. At 2 h, JA exhibited greater IVDMD than MA and AP (56% vs 44% and 48%, *P* = 0.01 and 0.02, respectively) (Figure 3). Forages harvested in FE also had greater IVDMD than MA (52% vs 44%, *P* = 0.02, respectively). After 4-h of digestion, JA had greater IVDMD than MA and AP (57% vs 46% and 51%, *P* = 0.01 and 0.04, respectively). Samples from JA had greater IVDMD than FE, MA, and AP after an 8-h incubation period (58% vs 50%, 49%, and 52%, *P* = 0.02, 0.01, and 0.04, respectively). At 24 h, IVDMD for JA was greater than FE, MA, and AP (63% vs 54%, 50%, and 45%, *P* = 0.01, 0.01, 0.01, respectively). During the same period FE IVDMD was greater than AP (54% vs 45%, *P* = 0.01, respectively). Following 48 h digestion, JA IVDMD was greater than FE, MA, and AP (72% vs 64%, 55%, and 61%, *P* = 0.03, 0.01, and 0.01, respectively). Furthermore, values for FE IVDMD were greater than MA (64% vs 55%, *P* = 0.01, respectively) at 48-h digestion.

After 2 and 4 h digestion periods, JA NDFD was greater than FE (16% vs 3%, *P* = 0.03; 19% vs 3%, *P* = 0.01, respectively) (Figure 4). Following 4-h digestion, NDFD was also greater for AP than FE (15% vs 3%, *P* = 0.04, respectively). At the 8-h digestion digestion time, JA, MA, and AP NDFD were greater than FE (20%, 16%, and 17% vs. 0.4%, *P* = 0.01, 0.01, and 0.01, respectively). Following 24 h of digestion JA NDFD was greater than FE, MA, and AP (31%, vs 9%, 19%, and 7%, *P* = 0.01, 0.04, and 0.01, respectively). The same differences were evident following 48 h with JA NDFD being greater than FE, MA, and AP (48% vs 32%, 27%, and 33%, *P* = 0.01, 0.01, and 0.01, respectively). Differences were detected for ADFD at both 8- and 24-h pull times. It was found that JA and MA were greater than FE (3% and 5% vs 0%, *P* =

0.03 and 0.01, respectively) (Figure 5). At the 24-h digestion time, MA was greater than FE (19% vs 2.5%, $P = 0.01$, respectively).

3.3.2 VFA and Gas Production

Following 48-h digestion, no differences in total VFA, acetate (A), propionate (P), valerate (V), or ratio of A+B:P+V were detected across treatments (Table 7). Butyrate (B) production of MA and FE forages were 48% and 42% greater than AP ($P = 0.01$ and 0.01). Isovalerate in JA, MA, and AP forages were 51%, 51%, and 46% greater than FE forages ($P =$ 0.01, 0.01, and 0.02). Ratios of A:P in JA forages were 26% greater than FE forages ($P = 0.03$).

Forage harvested in FE, MA, and AP produced 302%, 361%, and 290% greater concentrations of CH_4 than JA ($P = 0.01$, 0.01, and 0.01, respectively). Production of H^+ resulted in JA having 145% greater concentration than MA ($P = 0.03$). No other differences for CH_4 or H^+ were detected among treatments.

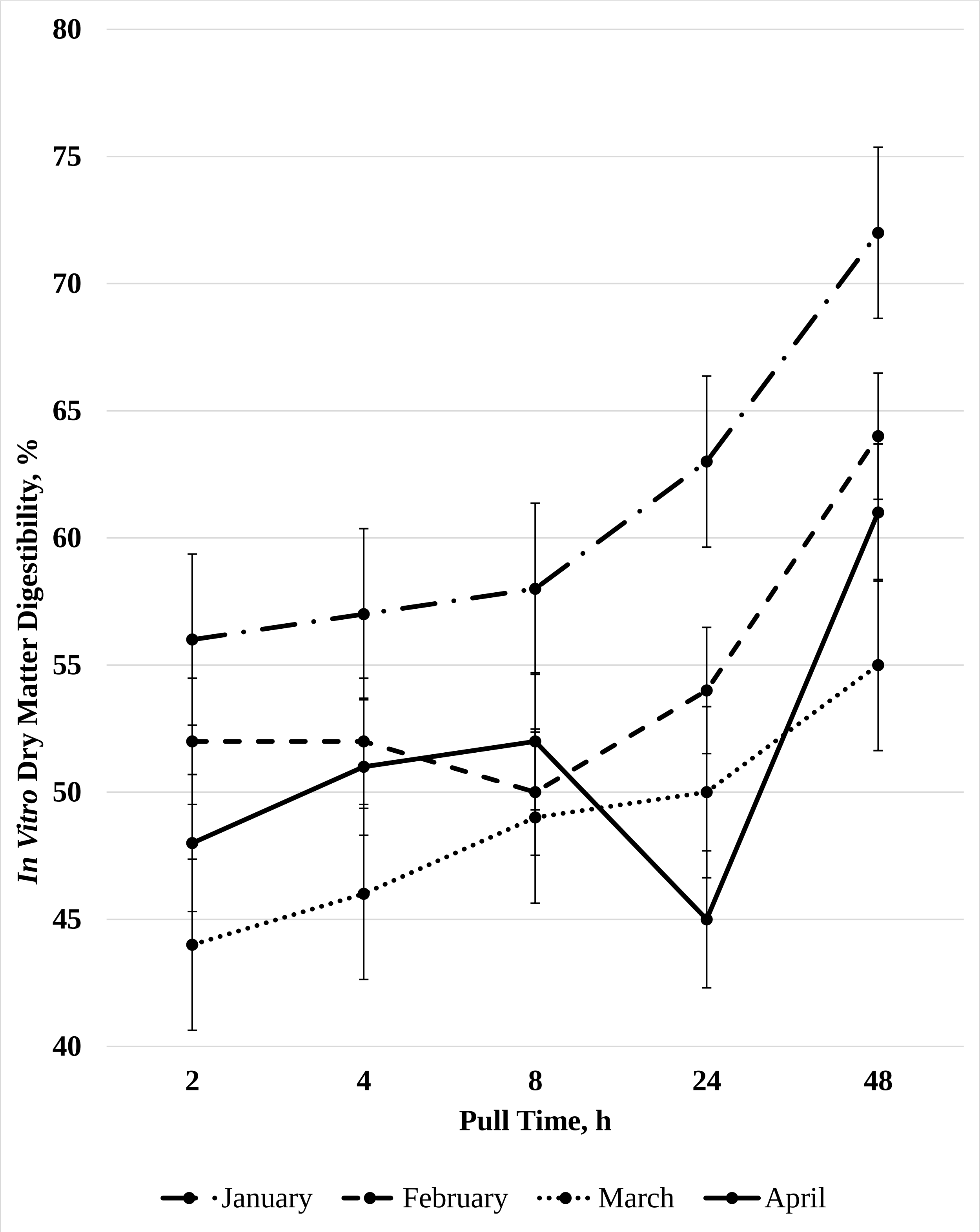

Figure 3. *In vitro* dry matter digestibility (IVDMD) of cool-season annual cover crops consisting of cereal rye, oat, crimson clover, and brassica following digestion after either 2, 4, 8, 24, or 48 h. Error bars indicate standard error of the mean.

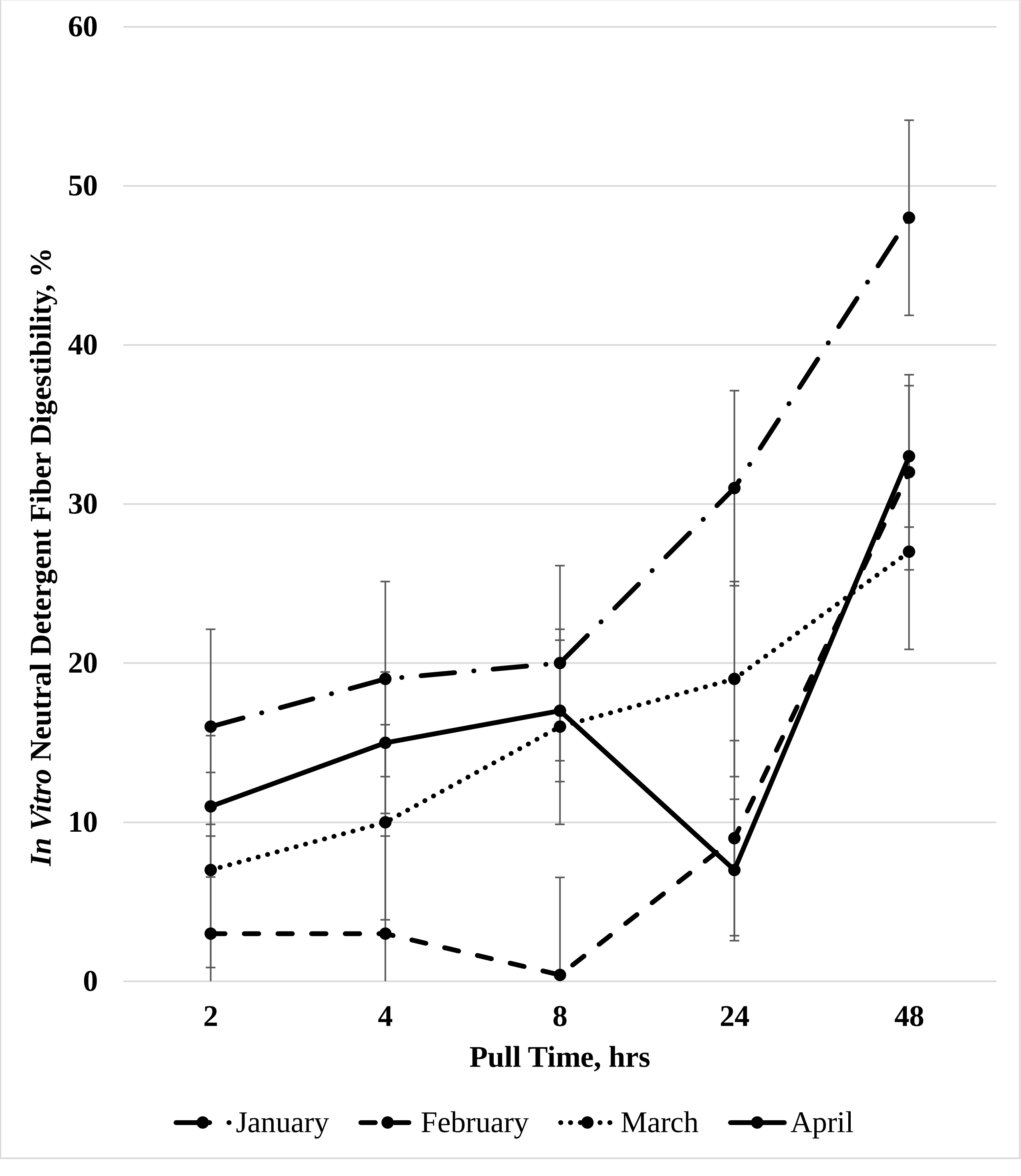

Figure 4. *In vitro* neutral detergent fiber digestibility (NDFD) of cool-season annual cover crops consisting of cereal rye, oat, crimson clover, and brassica following digestion after either 2, 4, 8, 24, or 48 h. Error bars indicate standard error of the mean.

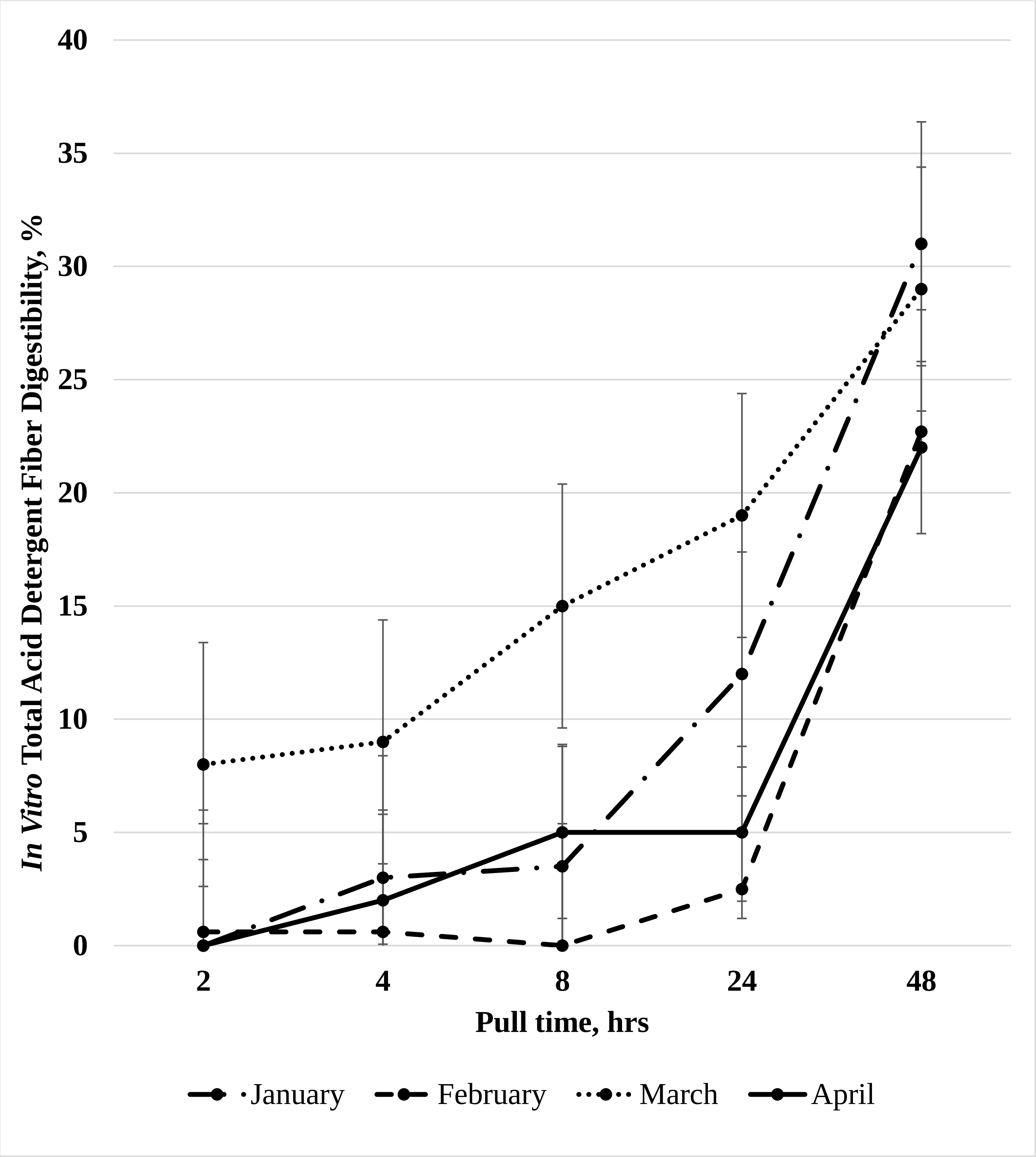

Figure 5. *In vitro* acid detergent fiber digestibility (ADFD) of cool-season annual cover crops consisting of cereal rye, oat, crimson clover, and brassica following digestion after either 2, 4, 8, 24, or 48 h. Error bars indicate standard error of the mean.

Table 7. Volatile fatty acid (VFA), methane (CH_4), and hydrogen (H^+) of cool season annual cover crops consisting of cereal rye, oat, crimson clover, and brassica harvested in either JA, FE, MA, or AP following 48 h digestion.

Item	**JA[1]**	**FE**	**MA**	**AP**	**SEM**
Total VFA, mM	50.6	54.3	53.8	48.0	2.90
Acetate (A)	34.8	37.3	36.0	33.2	1.95
Propionate (P)	9.4	10.8	11.0	9.8	0.71
Butyrate (B)	4.3^{ab}	4.7^{a}	4.9^{a}	3.3^{b}	0.37
Isobutyrate	0.45^{a}	0.30^{b}	0.35^{b}	0.37^{b}	0.03
Valerate (V)	0.89	0.60	0.74	0.71	0.11
Isovalerate	0.56^{a}	0.37^{b}	0.56^{a}	0.54^{a}	0.05
A:P	3.9^{a}	3.1^{b}	3.3^{ab}	3.7^{ab}	0.24
A + B:P + V	3.9	3.4	3.5	3.7	0.23
CH_4 (µmol/L)	80^{b}	322^{a}	369^{a}	312^{a}	65.41
H^+ (µmol/L)	5385^{a}	2803^{ab}	2195^{b}	2887^{ab}	102.6

[1] JA =January harvest; FE = February harvest; MA = March harvest; AP = April harvest

^{abc}Within a row, values without a common superscript differ ($P < 0.05$)

3.4 Discussion

3.4.1 Forage Digestibility

Forages harvested in JA had an IVDMD 8% greater than FE, 17% greater than MA, and 11% greater than AP harvested cover crops which is likely due to greater forage maturity and the increasing presence of fiber and lignin as the grazing season progressed. Weaver et al. (1978) reported that as corn (*Zea mays*) increased in maturity, its total digestibility decreased by as much as 20%. Forages in the fermentation time allotted followed the same pattern, but the full extent to which they were digestible was not reached. Digestibility values (IVDMD, NDFD, ADFD) did not plateau within any treatment in the current study meaning that there is potential for further forage digestion (Figures 3-5). Delayed digestion of NDF and ADF fiber fractions in the current study, paired with above average lignin values reported in the previous chapter, suggest that increased lignification decreased the rate of digestion within the system. Other studies, such as Marchant et al. (2019) reported nearly complete digestion of similar cool-season annual forages bred for grazing within a 48-h digestion period. Even though the limit of IVDMD was not determined in the current study, IVDMD values reported are similar to those reported by Dillard et al. (2019) which investigated the impacts of brassicas on forage digestibility and CH_4 production of cool-season forage mixtures. This study fermented forages using a continuous culture fermentor system over a 72-h period as opposed to batch culture for 48 h as in the current study. Values observed for NDFD and ADFD were 22 – 37% and 33 – 42% lower, respectively than those found in Dillard et al. (2019). Similar to IVDMD, NDFD and ADFD were still exhibiting exponential levels of digestion following 48 h of incubation. Although previous research from Van Soest (1994) states that forages should be reaching their full extent of digestion within 48-h, current results indicate that at least an additional 24-h of digestion is necessary to show the potential extent of IVDMD, NDFD, and ADFD in this forage mixture.

Although the forage species used were different, digestibility parameters are similar to Dillard et al. (2019). The current study utilized all cool-season annual forages whereas 50% of all forage treatments in Dillard et al. (2019) were orchardgrass (*Dactylis glomerata*), a cool-season perennial commonly used in the northern US. Marchant et al. (2019) determined IVDMD of different mixtures of wheat (*Triticum* aestivum), triticale (*Triticosecale*), and annual ryegrass (*Lolium multiflorum*) using the same methodology as the current study. This study reported IVDMD values that were 18 – 45% greater than those discovered in the current study. The inclusion of annual ryegrass in Marchant et al. (2019), likely increased digestion dynamics, whereas increased forage maturity of cereal rye is most likely associated with decreased IVDMD of the current system. In the previous chapter, grasses were the dominant forage among all treatments throughout the year. Although oat was included, cereal rye had greater presence than oat throughout all three years of the study.

The forages used in this specific cover crop system were all bred to mature early in the growing season. Specifically, FL401 cereal rye has been shown to produce increased biomass yields early in the grazing season with less production later in the spring (Dubeux et al., 2016). It has been reported that AU Sunrise crimson clover and T-raptor brassica follow similar growth patterns (Mosjidis et al., 2000; Denman et al., 2021), which partially explains the differences in IVDMD and NDFD among treatments. As forages become mature, the proportion of lignin present in the cell wall increases to support upward plant growth. Increased lignin results in lower digestibility of the NDF fractions and decreased animal performance. Increased proportions of lignin contribute to the delay in digestion of NDFD and ADFD. Presence of legumes and brassicas in the current study could also play a role in delaying digestion. Although legumes often contain less NDF than grasses, the percentage of indigestible NDF is greater in legumes than grasses (Sun et al., 2015). Likewise, brassicas have less total NDF than grasses, but have lessor concentrations of more digestible CWC that are found in grasses such as hemicellulose (Dillard et al., 2018). Increased presence of indigestible NDF fractions can reduce the rate at which digestion occurs. Although lignin is not digestible, it is often attached to cellulose and hemicellulose. Fibrolytic microbes can cleave cellulose and hemicellulose from lignin, but it requires time and energy from the rumen microbes. Short et al. (1974) reported that increased lignin negated other qualities of digestibility in forages. As lignin increases in proportion of CWC, the digestion of forages will decrease regardless of their cellular contents. Use of forages that have uniform production of biomass throughout a growing season will result in less mature stands early in the year, and more digestible forages throughout the grazing season.

3.4.2 VFA and Gas Production

Total VFA production in the current study was 56 – 88% less than values reported in Dillard et al., (2019). As previously stated, the current study took various measurements following 48 h of digestion as opposed to 72 h. Similar to digestibility, it can be assumed that total VFA production would increase following an additional 24 h of digestion. Individual VFA measurements follow the same pattern as total VFA production with each individual VFA being upwards of 100% lessor than values reported in Dillard et al. (2018) and Sun et al. (2015) which compared CH_4 production among forage mixtures containing either brassicas or legumes. Patterns of VFA distribution over time were similar to Weaver et al. (1978) and Chaves et al. (2006) although these studies used corn, native grasses, and various browse species. Although

IVDMD decreased as the growing season progressed, no differences in total VFA were detected. Other studies have attributed this phenomenon to increased rumen turnover time as a result of increased forage maturity. Mature forages require more time to digest and reduce indigestible particle size to a point that it can leave the rumen (Weaver et al., 1978). Current VFA results reinforce the need for additional digestion time of mature forages. Although no differences were present for A and P among treatments, the production potential of these two VFA are limited due to termination of digestion prior to asymptotic digestibility measurements.

Although a difference was present for A:P between JA and FE (Table 7), both values fall within the same range of biological significance. Overall, A:P was 72 – 116% greater in the current study than values reported in Dillard et al. (2018), which may have been due to differences in botanical composition of forage mixtures between the two studies. In the current study, grass accounted for 74% of the total sward while clovers and brassicas accounted for 14% and 10%, respectively. Although clovers were not used in Dillard et al., (2019) their diets consisted of a mixture containing either a 50/50 mixture of orchardgrass and annual ryegrass or orchardgrass and a brassica. Increased proportion of highly digestible forages such as brassicas and annual ryegrass will result in greater Propionate production due to higher availability of sugars for amylolytic bacteria. This relationship between diet and VFA production could explain differences in A:P between the two studies.

Although statistical differences were present for CH_4 production and H^+, total production was low to a point that biological relevance of these differences is minimal. Due to differences in laboratory equipment, comparison of these parameters with findings in other studies is difficult. Production of CH_4 was between 290 – 362% greater in FE, MA, and AP treatments than in JA. Inversely, JA H^+ production was 145% greater than in MA. These data paired with IVDMD indicate that younger, more digestible forage stands are more rapidly digestible and produce fewer greenhouse gases (GHG) within the rumen. Gas samples were taken prior to flattening of digestion curves. An additional 24 h of incubation may result in greater CH_4 production. The likelihood that an additional 24 h would produce CH_4 levels comparable to Dillard et al. (2018) or Sun et al. (2015) are low.

3.5 Conclusions

Digestibility of cool-season cover crops is suitable for various classes of grazing cattle throughout the growing season. Although IVDMD was less in forages harvested later in the year, all forages tested in the current study exhibited acceptable digestibility by the 48-h timepoint according to Beef NRC (2016) recommendations. Limited conclusions can be made in regard to the extent that cool-season cover crops can be digested. Although current data indicate that as the growing season progresses, forage digestibility will decrease, it is unknown if after 72 h if forages harvested throughout the season will be adequate for stocker cattle or cattle with lower nutritional needs. Production of VFA is adequate for various classes of beef cattle. Similar to IVDMD, it can be concluded that digestion for 72 h will increase total and individual VFA, but the extent they are increased is unknown. Production of CH_4 is minimal in the current system. This data indicate that little air quality concerns are present in the current system due to the low concentration of CH_4 produced. Overall, the cover crop mixture evaluated herein shows potential for an alternative source of moderate to high quality forage that could replace supplemental feeding in the winter with little to no environmental risks as a result of rumen fermentation. Further research is needed to determine the time at which these cool-season cover crops are fully digested. This information, as well as corresponding VFA and GHG data, will give stronger indications of the value of grazed cover crops in ruminant diets.

Implications

Grazed cover crops can be a useful management tool for row crop and livestock producers when properly managed. This system allows for grazing of land that otherwise would be void of any livestock. The use of grazed cover crops increases efficiency of land use and greater production output per hectare for producers as a result of cattle income potential. Specific management considerations should be made when grazing cover crops, however. Cover crops typically consist of high-quality forages that are suitable for continuous grazing of stocker cattle. Data from Experiment 1 indicate that adjustments to forage allowance and stocking density must be made throughout the grazing season in order to ensure that cattle are able to meet DM intake requirements over an extended period of time. The second experiment illustrates that digestion of cover crop forages requires greater amounts of time to fully digest than other common forages used for stocker cattle production such as annual ryegrass. In both trials, the primary issue inhibiting production output was the early maturity of the species and varieties of forages in the cover crop system. Multiple regression indicated that NDF had the greatest influence on ADG. Mature forages also exhibited the lowest IVDMD, NDFD, and ADFD. In order for producers to obtain the full value of cover crop systems they must increase forage allowance while maintaining vegetative forage stands in order to mitigate reduced animal performance due to limited digestibility of cell wall constituents in overly mature forages.

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