

Effects of Grazing Cool-Season Annual Mixtures on Cover Crop Performance and Soil Health

by

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ABSTRACT

Grazing cool-season annual cover crops is a viable strategy to extend winter forage availability while supporting soil and cropping system sustainability. A two-year study was conducted at the Wiregrass Research and Extension Center (Headland, AL) to evaluate the effects of grazing multispecies cover crops on forage yield, nutritive value, botanical composition, soil nutrients, and steer performance within a cotton–peanut rotation. Twelve 0.6-ha paddocks were planted with a mixture of oat, crimson clover, and brassica and managed under grazed or ungrazed conditions. Botanical composition varied among treatments, with mixed-species paddocks exhibiting lower weed presence than monocultures. Forage yield was not affected by grazing, indicating that moderate winter grazing did not reduce biomass production. Grazing reduced neutral detergent fiber concentrations, suggesting improved forage quality, while crude protein remained unchanged. Steer average daily gain and gain per hectare were similar across treatments, demonstrating adequate animal performance. Soil nutrient concentrations were largely stable, although nitrogen and potassium responded to grazing and treatment interactions. Overall, moderate grazing of multispecies cover crops sustained livestock productivity while maintaining forage and soil performance.

Artificial Intelligence (AI) Use Disclosure

In the preparation of this thesis, the following Artificial Intelligence (AI) tools were used: ChatGPT (OpenAI). These tools were used primarily to assist with grammar editing, sentence clarity, paraphrasing for academic style, and formatting guidance. The author acknowledges full responsibility for the intellectual content of this work and has ensured that all AI-assisted sections have been carefully reviewed and revised for accuracy and appropriate academic style. All AI-generated content was reviewed and validated for relevance, appropriateness, and accuracy before incorporation into the final document to maintain the scholarly integrity of this research.

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LIST OF ABBREVIATIONS AND SYMBOLS

The author has made all efforts to observe the accepted abbreviations for Journal of Animal Science and Applied Animal Science as these are potential outlets for publication. The following list provides the abbreviations accepted by these journals as well as additional acronyms or abbreviations used throughout this document:

Abbreviation	Definition
ADG	average daily gain
ADF	acid detergent fiber
AOAC	Association of Official Analytical Chemists
BCS	body condition score
BW	body weight
C	carbon
CC	cover crop(s)
CP	crude protein, calculated as nitrogen times 6.25.
D	digestible fraction
d	day(s)
DM	dry matter
G	grazed
ha	hectare(s)
hd	head
IVDMD	in vitro dry matter digestibility
K	potassium
N	nitrogen
NDF	neutral detergent fiber
NPSP	nonpoint-source pollution
P	phosphorous
PLS	pure live seed
SAS	SAS Institute, Inc. (formerly known as Statistical Analysis System)
SEM	standard error of the mean
SOM	soil organic matter
TDN	total digestible nutrients

Chapter I. Literature Review

1. Introduction

The practice of managing cover crops (CC) between cash crops is one of the oldest farming techniques in existence and is currently receiving renewed interest globally (Romdhane et al., 2019). The term CC refers to any plants cultivated for reasons other than primary grain or forage production, and they are typically categorized into leguminous broadleaves, non-leguminous broadleaves, and grasses. Many studies have shown the benefits of CC in agricultural production, with numerous investigations concentrating on their effects on soil physical, chemical, or biological properties (Adetunji et al., 2020).

Saleem et al. (2020) proposed that the increased root growth of CC could provide several soil benefits, including enhancing soil organic carbon (C) levels, improving nutrient availability, and promoting soil aggregation. In addition, CC help prevent soil erosion, improve water retention, control weeds, and enhance biodiversity. By contributing organic matter, CC improve soil structure and support nutrient cycling, which reduces the need for synthetic fertilizers. These ecological advantages, along with increased crop yields, make CC a valuable tool in agriculture. Although they require an initial investment, CC are considered a long-term strategy that offers benefits over time by reducing costs, improving farm management, and increasing farm resilience (SARE, 2015).

In addition to their environmental and productivity benefits, CC also play a significant role in the economic viability of farms, particularly in the southeastern U.S. According to USDA (2016) the adoption of CC has steadily increased across the country, with notable growth in regions such

as the Southeast. This region, which faces challenges such as heavy rainfall, soil erosion, and fluctuating weather patterns, has seen CC become an essential tool for improving soil health, managing water, and reducing the need for synthetic fertilizers. These benefits contribute to long-term farm profitability, offering farmers in the Southeast a cost-effective strategy for managing environmental stressors and improving the sustainability of their farming systems.

Across the world, farmers are working to incorporate CC into diverse cropping systems for improved system sustainability under both conventional and organic management (Clay et al., 2020). Consequently, there is a huge need for answers regarding the uncertainties surrounding the species and mixture selection of CC as well as the impact of CC management on soil attributes. Interest is increasing in the use of CC mixtures, but information on water runoff and nitrate leaching comparing monocultures and mixtures of CC is limited (Wortman et al., 2012).

2. Importance of cover crops

2.1 Soil compaction

Soil compaction is a significant challenge in agriculture, especially when heavy machinery is used on wet soils, reducing pore space and impairing root growth, nutrient uptake, and water drainage (Cadillac, 2019). Mechanical methods to remove compacted soil layers are costly and energy-intensive, so an alternative could be using plants with strong root systems to break up the compacted subsoil. These deep roots penetrate compacted layers, creating channels that improve water infiltration and aeration, facilitating root movement for subsequent crops (Dexter, 1991). Cover crop root traits are essential to agroecosystem functions, particularly soil C and nutrient cycling. Legume species contribute new nitrogen (N) through biological N fixation, while fibrous, fine roots from grass species are vital for nutrient scavenging and recycling (Blanco-Canqui et al., 2015). When grown in mixtures, complementary root traits lead to increase above-

ground yields and root biomass (Brooker et al., 2015). Recent field evidence also shows that extending grazing periods on cover crops can negatively affect some physical soil indicators—raising penetration resistance and reducing water-stable aggregates—highlighting the need to balance stocking rate and timing to avoid compaction (Reiter et al., 2024).

Additionally, strategies like incorporating CC that decompose to contribute organic matter can improve soil aggregation, structure, and porosity by binding soil particles into aggregates, reducing compaction (Six et al., 2006). A rich incorporation of CC plays a vital role in maintaining soil fertility and productivity, increasing crop yields while reducing environmental impacts.

2.2 Soil nutrients

Cover crops can help manage N in agricultural soils by altering the cycling and availability of N. According to (Kaspar et al., 2011), nitrate (NO_3) in soil is highly soluble and can be lost through water movement, often reaching surface waters via drainage systems. Living plants help reduce nitrate leaching by absorbing both nitrate and water, which lowers its concentration in the soil and reduces water movement through the soil. This process helps minimize N loss in agricultural systems. In studies reviewed by (Meisinger et al., 1991), CC reduced both the mass of N leached and nitrate concentration of leachate by 20 to 80% compared with no CC control. They also determined that grasses and brassicas were two to three times as effective as legumes in reducing NO_3 leaching. (Amossé et al., 2013) found that 71% to 96% of N in the biomass of ground cover plants came from symbiotically fixed N, enriching the soil by 38 to 67 kg N /ha. Legume CC, which typically have a C:N ratio below 20:1, promotes quicker N mineralization. By combining deep-rooted and legumes, farmers can effectively address soil compaction and improve overall farm resilience.

When planted during fallow periods, CC modify the typical seasonal patterns of N uptake and mineralization. Successful N management with CC involves timing N availability so that inorganic N is accessible during active crop growth and minimal when crops are not growing, thus reducing N loss to the environment.

In addition, soil productivity is strongly influenced by soil organic matter (SOM) and its main component, soil organic C. Soil organic matter stabilizes soil aggregates, makes soil easier to cultivate, increases aeration, and increases soil water holding and buffering capacities; SOM breakdown releases available nutrients to plants (Carter and Stewart, 1996). The content depends on soil type, frequency and type of cultivation, cropping and residue management, and fertilizer N input (Schimel et al., 1994; Heenan et al., 1995; Grace et al., 1995; Webb et al., 2003; Bhogal et al., 1997).

Sequestering C in SOM is a key strategy for reducing atmospheric CO₂ concentrations (Lal et al., 1999). Soil organic matter consists of soil humus, along with plant, animal, and microbial residues, and is typically composed of 50 to 58% C by mass (Nelson & Sommers, 1996). Aside from the impact of CC on C and N cycling in soil, there is limited information regarding their impact on other nutrients or soil pH (Kaspar et al., 2011).

2.3 Water runoff/leaching

Reducing runoff sediment and nutrient loss as well as nutrient leaching from croplands is a high priority to mitigate nonpoint-source pollution (NPSP) of water sources, maintain soil fertility, and improve overall soil and water quality. The delay in the initiation of water runoff with CC is attributed to the CC-induced improvement in soil properties as well as to the increased soil surface roughness from the growing CC and CC residues (Blanco-Canqui et al., 2013). Adoption of CC can be a reemerging strategy to address these concerns and the increase

time to runoff start by 10 to 40 min and reduce both runoff volume by 10 to 98% and sediment loss by 22 to 100% (Blanco-Canqui et al., 2015).

The relative impact of CC on soil water available to the following crop depends on several factors, including cover crop management, the timing and amount of precipitation, and the total water-holding capacity of the root-accessible portion of the soil profile (Frye et al., 1988). In fields with subsurface drainage systems, CC can reduce drainage volume during the spring before cash crops are planted (Qi and Helmers, 2010), which helps minimize nitrate losses (Kanwar et al., 2005). An increase in root growth beneath CC can play a key role in enhancing water infiltration and minimizing soil erosion (De Baets et al., 2011). After a CC is terminated, its residues remaining on the soil surface can boost residue cover, decrease evaporation, and improve soil water retention (Waggoner and Mengel, 1988).

The impacts of CC on water erosion has often placed emphasis on runoff and sediment losses, but not much on losses of soluble or dissolved nutrients in runoff including total phosphorus, $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, and dissolved P (Blanco-Canqui et al., 2013). Several studies have demonstrated that soluble P can be lost through runoff flowing over plant residues (Timmons et al., 1970; Bechmann et al., 2005). Overall, total N and P concentrations were reduced by CC only in one of the eight studies and differences in the concentrations of $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, and dissolved P were found in only two out of eight studies. The few studies suggest that CC can reduce nutrient losses in less than 25% of cases (Blanco-Canqui et al., 2013). However, over the course of a year, the presence of CC is expected to enhance plant water uptake and infiltration, which should help reduce runoff volume. According to Dabney (1998), CC reduce the sheer force of runoff water by decreasing volume through enhanced infiltration; this happens because CC prevent surface sealing, boost water storage capacity, and improve soil structure. The N

absorbed by winter CC would not impact N availability for cash crops if that N would have been lost through leaching or gaseous emissions, or if it is replenished through mineralization or fertilization (Kaspar et al., 2011).

2.4 Weed control

The contribution of CC to weed management is not well established. In theory, weed control could be improved if a controllable CC were able to replace an invasive weed population in the agroecosystem (Teasdale, 2013). The main objective of using CC for weed control is to replace an uncontrollable weed population with a manageable CC. According to Holderbaum et al. (1990), interannual CC are most suitable for regions where there is enough time for establishment in the fall and where soil moisture is not a limiting factor in the spring. These conditions allow the CC to effectively grow and provide their benefits throughout the season.

Weed control is species-specific, and CC residues tend to suppress the emergence of certain weed species more than others (Putnam and DeFrank, 1983). Despite the reduction in weed emergence caused by CC residues, the number of weed seedlings that emerge is often enough to effectively compete with crops and reduce yields when no herbicides are used (Wicks et al., 1994). Increasing seeding rate of the CC species could increase the biomass production and soil surface cover needed for greater weed suppression (Brennan and Smith, 2005; Ryan et al., 2011). For example, increasing the seeding rate of a CC by three times the standard rate reduced weed biomass from 300 to <100 kg/ha (Brennan et al., 2009). Weed biomass may be less affected by residue than weed density, as weeds often compensate for lower density by producing greater biomass per plant (Carson et al., 1990).

Studies have indicated that the timing of CC planting, whether in the fall or spring, affects CC biomass production, which in turn influences the level of weed suppression. Generally,

earlier planting leads to more effective weed control (Saini et al., 2006; Anugroho et al., 2009; Wells et al., 2016; Sturm et al., 2017). Equally important is the timing of termination; for example, delaying the termination of crimson clover (*Trifolium incarnatum* L.) by four weeks led to a tenfold increase in biomass and substantially improved weed suppression (Saini et al., 2006). In this study, annual ryegrass (*Lolium multiflorum* L.) biomass increased by 37 to 100% when terminated 10 to 14 d after the early rye (*Secale cereale* L.) termination date, with subsequent increases in weed suppression (Mischler et al., 2010; Mirsky et al., 2011; Nord et al., 2012). Delaying the planting of the main crop after terminating the CC may lead to reduced weed suppression during the growing season. This decline is anticipated because the CC residue breaks down over time, diminishing its ability to suppress weeds as the main crop develops.

Overall, CC residues are likely to provide weed suppression during the early season but may not offer full-season control. Therefore, an accurate assessment of the potential for weed suppression and herbicide reduction, in comparison to other possible benefits like improved soil fertility, is essential. This evaluation will help determine whether reducing herbicide use should be a primary goal of CC management or whether herbicides should be viewed as a tool to enhance other benefits of CC (Teasdale, 2013).

2.5 Cover Crop Termination

According to Kelton (2015), typical termination practices for CC include treating the crop with a nonselective herbicide (glyphosate or paraquat) 2-4 weeks prior to the primary crop plant date and leaving standing residue as a cover. Mechanically rolling or crimping plant residue, used in conjunction with termination herbicides, is another option for effectively managing CC prior to planting on a peanut rotation. Although rolling CC residue offers numerous benefits,

there are concerns about the increased interception of preemergent herbicides by a thick layer of plant material covering the soil surface.

3. Cash crop performance with winter cover crops

3.1 Cotton

Cotton (*Gossypium hirsutum* L.) is a key global crop valued for its economic significance. It is extensively used in the textile industry, as well as for producing cottonseed oil and animal feed (Snapp et al., 2005). It is estimated that the average lint yield of upland cotton in the US has increased by more than 90% over the last six decades (USDA- NASS, 2023). Incorporating CC into cropping systems introduces both direct and indirect costs and benefits for the farm. The costs associated with using CC may involve higher direct expenses for planting and management, potential revenue loss if CC hinder cash crop production, delayed soil warming, and challenges in forecasting N mineralization (Snapp et al., 2005).

Traditionally, most cotton producers in the Southeast have relied on conventional tillage methods for planting. However, due to soil degradation and other issues associated with conventional tillage, many farmers have transitioned to conservation tillage practices, such as no-till or reduced tillage, and incorporated winter CC into their systems (Morton, 2016).

In recent decades, cotton breeding programs have made significant genetic improvements in lint yield, with annual increases ranging from 2 to 18 kg/ha across cultivars worldwide (Conaty et al., 2020; Singh et al., 2023, 2024; Zhang et al., 2019). Moreover, the introduction of improved cotton cultivars has been linked to an increase in fertilizer use , with a 36% rise in N, an 8% reduction in P, and a 16% increase in potassium (K) over the past six decades to optimize yield (Fageria et al., 2008; Pabuayon et al., 2021, 2020; USDA-ERS, 2023; USDA-NASS,

2023). During this period, the average yield of upland cotton in the U.S. grew by 94% from 1960 to 2018.

In addition to enhancing the yield of cash crops like cotton, it is essential to protect overall soil health from extreme weather events, such as heavy rainfall. This is particularly important in the southeastern United States, where intense winter precipitation can lead to significant erosion (Blanco-Canqui, 2022, 2018; Endale et al., 2014; Johnson et al., 2021). The use of winter CC is a practical strategy to enhance soil organic C and mitigate the effects of rainfall events. Although CC have been shown to increase soil C, evaluating changes in soil organic C across cropping systems is complex due to considerable variations in soil organic C at different depths and locations (Kaspar et al., 2011).

3.2 Peanut

Peanut (*Arachis hypogaea* L.) is a warm-season legume well adapted to the southern United States—especially the tri-state peanut belt of southwest Georgia, southeast Alabama, and northwest Florida—where long growing seasons and sandy Coastal Plain soils favor production. Planting typically occurs after the last frost once soils warm (ideal late April–late May; soil a 10 cm > 20 °C/68 °F), and the crop generally requires ~140–150 days to maturity; harvest timing also depends on adequate soil moisture for digging and inversion to minimize losses (UGA, 2024; Clemson HGIC, 2023; UGA Field Report, 2025).

The United States is among the world's top producers commonly ranked 4th behind China, India, and Nigeria within a global output of roughly ~50–54 million metric tons in recent seasons (USDA-ERS, 2023; FAOSTAT/Yearbook, 2023; UGA Field Report, 2025). Most of the U.S. peanut production is destined for edible consumption, with only about 15% processed into

peanut oil. Additionally, the U.S. exports 200,000–250,000 metric tons annually, mainly to Canada, Mexico, Europe, and Japan (FAO, 2018; American Peanut Council, 2017).

Peanut yields are often limited by factors such as drought, pests, diseases, poor agronomic practices, and low-performing cultivars. Advances in genetic engineering have helped address some of these constraints by improving resistance and yield potential (Sharma et al., 2007). Conservation agriculture systems have also gained popularity for peanut production due to their benefits in reducing labor and tillage costs (Price et al., 2015). Because peanut is already widely grown in the southeastern U.S., it presents an economic advantage in terms of seed availability and potential re-seeding capacity (Jaramillo et al., 2018).

Peanuts are typically cultivated on sandy soils, which are highly erodible. To mitigate erosion and enhance soil structure, cover cropping is widely adopted. Common cover crops used prior to peanut planting include small cereal grains such as rye and wheat (Wright et al., 2009). Rye provides high biomass and dense rooting, which aid in soil coverage and weed suppression (Kuo et al., 1997; Sainju et al., 1997; Williams and Weil, 2004). Leguminous cover crops can add N to the soil through biological fixation, although their use prior to peanuts must be carefully managed, as both peanut and legume covers share similar nutrient demands (Tubbs, 2003; SAN, 2007).

Nutrient management plays a key role in peanut productivity and quality. Although peanut is a nitrogen-fixing crop, calcium (Ca) remains the most yield-limiting nutrient due to its essential role in pod filling. Calcium deficiencies result in “pops” — unfilled or aborted pods — which directly reduce yield (Cox et al., 1982). Boron (B) is another crucial micronutrient affecting kernel development and quality. Inadequate B levels can lead to “hollow heart,” a disorder that

impacts the marketability of the nuts. While B does not influence yield quantity, it significantly affects yield quality. Deficiencies are common in soils testing below 0.05 mg B/kg (SAN, 2007).

Phosphorus is frequently deficient in unfertilized soils but can be effectively corrected through phosphate application. Peanut requires only moderate levels of P (as low as 4 mg kg⁻¹) due to minimal fixation in sandy soils. Cobalt (Co), though not essential to the plant itself, is important for rhizobia nitrogen fixation and may be applied as a seed treatment or foliar spray. Other nutrients such as potassium, sulfur (S), magnesium (Mg), manganese (Mn), and zinc (Zn) are necessary for overall plant development but have limited direct impact on pod yield. To optimize nutrient availability, lime CaMg (CO₃)₂ is often applied to maintain soil pH between 6.0 and 7.0 (Hallock et al., 1971).

4. Cover crop species

4.1 Oat

Oat (*Avena sativa* L.) is a cool-season annual cereal grain widely grown in the Southeast for both grain and winter forage. Known for its palatability, oats are often favored by cattle in mixtures, though they have limited grazing tolerance, which is why planting them in mixtures helps extend forage availability over a longer period (Ball et al., 2015; Hancock, 2019). This adaptability in diverse cropping systems highlights its importance not only as a crop that contributes to agricultural productivity but also as a tool for improving soil health and conservation. Oat is known to thrive in various climates, improving soil structure, increasing organic matter, and reducing soil erosion when included in crop rotations. Moreover, its high water-use efficiency and nutrient cycling capabilities make it a key component of sustainable farming practices.

Oat grows best in well-drained, fertile soils and is susceptible to winter kill from severe frosts (Ball et al., 2015). When grown under favorable conditions and with proper management, oat can produce up to 4,480 kg DM/ha in late summer or early fall and 8,970 kg DM/ha in spring (Clark, 2012). In the Southeast, planting typically occurs between early September and late October (Ball et al., 2015).

The successive developmental stages of the oat plant, including tillering, booting, and heading, play a critical role in optimizing management practices such as grazing and termination, which are essential for balancing forage quality and ground cover. Understanding these stages is vital for successful oat management (Bonnett, 1961). Planting methods also affect crop success—drilling seeds provides more accurate placement, reducing seeding rates, while broadcasting requires higher seeding rates to compensate for uneven seed distribution.

Recommended seeding rates are 112 kg pure live seed (PLS)/ha for monoculture and 67 kg PLS/ha for mixtures (Massey, 2016). The planting depth should not exceed 3.8 cm, and fertilization should follow soil test recommendations for lime, phosphorus (P), and potassium (K). A split application of nitrogen (N) fertilizer is recommended, with some applied shortly after planting to promote tillering and stand density, and again in mid-winter to boost spring forage production. Typical N rates range from 45 to 56 kg N/ha (Hancock, 2019).

In addition to its growth benefits, oat is less susceptible to pest damage compared to wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*), although it can still be affected by grain aphids, fall armyworms, thrips, and other pests. Studies comparing small grain silages with corn silage found that oat silage contains 9.8% crude protein (CP), 60.7% total digestible nutrients (TDN), 31.2% crude fiber, and 40.2% dry matter (DM) (Schroeder, 2004). Another study found oat silage to contain 12.6% CP, 42.3% acid detergent fiber (ADF), 31.2% crude fiber, and 30.1%

DM (Oltjen and Bolsen, 1980). These nutritional profiles highlight oat silage as a valuable feed option in comparison to other small grain silages.

4.2 Crimson clover

Crimson clover is the most widely used legume cover crop across the United States (CTIC, 2016). It is a fast-growing, cool-season annual legume that produces a high biomass, making it an excellent choice for improving soil structure, enhancing nitrogen fixation, and reducing soil erosion when incorporated into crop rotations (Ball et al., 2015).

In the Southeast, crimson clover is typically planted in late summer or early fall and may reseed itself in subsequent years. The recommended planting rates are 11 to 17 kg PLS/ha for monoculture and 6 to 11 PLS/ha when planted in a mixture (Clark, 2012). It is the earliest maturing and highest-yielding among the cool-season annual clovers (Knight, 1985). As a legume, it can fix N, potentially adding 80 to 150 kg of N/ha in a single growing season under optimal conditions (Seeds, 2018). In Southeastern U.S., crimson clover is often cultivated as a forage crop and can be grown as either a winter or summer annual, depending on regional climate conditions (Clark et al., 2007). It matures earlier than other cool-season annual clovers, making it the most productive in this group (Knight, 1985). Crimson clover is sensitive to both heat and cold, thriving in soils with a pH between 6.0 and 7.0 (USDA, 2009). It is primarily used as a cover crop or in mixtures for grazing or hay production. It yields between 3,923 and 6,165 kg DM/ha and grows to a height of 30 to 91 cm (Clark, 2012; Ball et al., 2015).

For effective nitrogen fixation with Rhizobia, crimson clover requires adequate levels of phosphorus (P) and potassium (K). Although nitrogen (N) fertilization is not always necessary, P and K fertilization should be based on soil test recommendations to optimize growth and fixation capacity. Excessive nitrogen application should be avoided, as it can promote grass

competition, which may reduce clover yields in grass-legume mixtures. As a legume, crimson clover can fix between 80 to 150 kg of N/ha in a single growing season when conditions are ideal (Seeds, 2018).

This CC thrives best in well-drained soils and tends to perform poorly on dry, sandy, or poorly drained sites. Notably, crimson clover outperforms other clovers in cooler temperatures, producing more forage during colder months. Clark et al. (2007) stated that it is also tolerant of acidic soils, which makes it suitable for planting in mixtures with small grains or annual ryegrass. Additionally, crimson clover is frequently seeded into warm-season perennial grass pastures, such as bermudagrass (*Cynodon dactylon* L.) and bahiagrass (*Paspalum notatum*) and may even reseed under specific management practices (Clark et al., 2007).

A case study conducted in West Virginia demonstrated that planting a crimson clover CC before a corn silage crop improved profitability, achieving a 10% savings when the clover was incorporated, compared to side-dressing with urea-ammonium nitrate at the standard rate of 134.5 kg/ha (Wickliffe and Rayburn, 2008). As a green manure, crimson clover is highly effective in suppressing weeds and can contribute 79 to 168 kg per ha when allowed to reach the late bloom stage before being terminated (Ball and Lacefield, 2000; Clark, 2007).

In terms of livestock use, crimson clover is a highly nutritious forage, containing over 25% CP and offering 80% digestibility during its early spring growth (Akin et al., 1982). Even at full bloom, it still provides between 12 to 14% CP and 60 to 65% TDN on a DM basis (Ball and Lacefield, 2000; Harper, 2004). It does not perform well in poorly drained or highly alkaline soils (Clark, 2007; Knight, 1985). Crimson clover seed is readily available from commercial suppliers, with both common and improved cultivars offered. Cultivars should be selected based on local variety trial data, with early-maturing types being ideal for over-seeding summer grass

sod to reduce competition, as well as for green manure crops to allow early spring termination (Ball and Lacefield, 2000).

4.3. *Brassica species*

Brassicas (*Brassica* spp.) are cool-season annual forages known for their ability to produce high yields and excellent nutritional quality. Common brassicas used as forage for livestock include turnips (*Brassica rapa* L.), kale (*B. oleracea* L.), radish (*Raphanus raphanistrum* L.), and hybrids like T-raptor (*B. rapa* L. × *B. napus* L.; Dillard et al., 2018). The planting dates for forage brassicas vary based on factors such as climate, location, and the desired DM yield. In the Southeast, brassicas are generally planted between August and October, with the intent to graze them during the winter months, harvest them for green chop, or store them as baleage if grown in mixed stands (Ball et al., 2015). These forage crops are both cold and drought-tolerant, maintaining their nutritional value even as temperatures drop in the colder months (Wilson, 2013).

Brassicas generally exhibit high in vitro dry matter digestibility (IVDMD), ranging from 65% to 80% and CP concentrations between 20% and 30% (Lemus, 2009; Dillard et al., 2017). These forages have a higher proportion of fermentable carbohydrates compared to structural carbohydrates, while still preserving a significant CP content (Barry et al., 1981). Brassicas have a high leaf-to-stem ratio (about 95:5), with most of their nutrients concentrated in the leaves, making them highly beneficial for cattle and sheep. Even the roots of brassicas are rich in nutrients, with turnip and swede roots containing CP levels ranging from 10% to 14% (Lemus, 2009). Although roots are not typically harvested or grazed, they may be consumed if cattle pull them from the base of the plant.

Brassicas are more tolerant of lower soil pH levels, like grasses rather than legumes. They can thrive in soils with pH levels ranging from 5.3 to 6.8 (Lemus, 2009). Phosphorus and K fertilization should be based on soil test results to ensure proper nutrient application. Fertilizers containing sulfur or sulfate should be avoided for brassicas, as they already have a high sulfur concentration, which can affect plant metabolism and reduce nutrient efficiency (Lehmkuhler, 2014).

The optimal row spacing for brassicas is between 15 and 20 cm, with a planting depth no greater than 2.5 cm to achieve the highest germination rates (Wilson, 2013). Seeding rates vary by variety but typically range from 4.4 to 11 kg PLS/ha (Ayres and Clements, 2002). In a study comparing nine brassica varieties, DM yield ranged from 9,482 kg DM/ha to 3,441 kg DM/ha, depending on the planting date (Villalobos and Brummer, 2015). Overall, brassicas can yield between 1,500 and 5,000 kg of DM/ha, regardless of the species (Griffin et al., 1984; Simon et al., 2013).

5. Importance of cool-season annual forages in grazing cattle

5.1 Forage quality and quantity

Many cool-season annual CC monocultures and mixtures are designed primarily to maximize above-ground biomass production. To deliver ecosystem benefits, CC need to generate sufficient aboveground biomass to shield the soil from weather extremes like heavy rain or drought (Plainisich et al., 2021). This plant biomass may also serve as an additional grazing resource for livestock like beef cattle. Forage accumulation is largely influenced by factors such as establishment methods, plant selection, and grazing intensity (Edwards and Chapman, 2011; Franzluebbbers and Stuedemann, 2014). However, studies have indicated that neither the method

of establishment nor the choice of CC species significantly impacted total forage yield (Franzluebbers and Stuedemann, 2014). Grazing season costs can be minimized by incorporating perennial pastures and annual forages. Traditionally, oat and fall rye have played a modest role in helping to extend the grazing period (McCartney et al., 2008). Annual cool-season crops show promise for supplementary grazing systems.

Several studies suggest that using forage mixtures can result in higher biomass yields compared to single-species plantings. For example, Sanderson et al. (2018) observed that cool-season annual mixtures produced 30% to 60% more dry matter (DM) than monocultures of the same species. This research, conducted in North Dakota (a region characterized by cooler and drier conditions than the Southeastern U.S.), utilized spring planting rather than fall. These climatic differences may have favored the growth of brassicas and legumes, which are generally more susceptible to frost and winterkill when planted in the fall.

Yield outcomes vary depending on the specific combination of plant species. Villalobos and Brummer (2017) found that mixes including small grains, legumes, and brassicas could yield over 5,000 kg DM/ha when not grazed. While these mixtures produced slightly less biomass than small grain monocultures, they delivered adequate forage and contributed positively to ecosystem functions, such as nitrogen recycling and improved soil structure. Additionally, (Carrell et., 2022) demonstrated that grazing cool season cover crops can reduce winter supplementation needs for cattle, though extended grazing periods may not be as advantageous when managed under continuous grazing for stocker cattle production.

In terms of forage quality, the inclusion of legumes and brassicas in mixtures was shown to improve nutritional value. Villalobos and Brummer (2017) reported that such mixtures had greater CP concentrations (18% compared to 14%) and significantly lower neutral detergent fiber

levels (22% vs. 57%) than monocultures of small grains. These results underscore the value of diverse mixtures in enhancing forage quality.

Mason et al. (2019) explored the effects of overseeding Eastern gamagrass (*Tripsacum dactyloides* L.) with cereal rye alone or in combination with red clover (*Trifolium pratense*) in western Alabama. Their findings showed no impact on herbage yield, CP levels, or IVDMD. Similarly, Deak et al. (2007) examined whether the number of species in a forage mixture influenced nutritive value. They found no substantial differences in CP or IVDMD between 2-species mixtures (one perennial grass and one clover) and more diverse 9-species mixtures composed of multiple grasses and clovers. The dominance of certain grass species, particularly orchardgrass (*Dactylis glomerata* L.) and tall fescue (*Schedonorus arundinaceus* Schreb.), was suggested as a possible explanation for the lack of variation. Notably, the presence of clovers was responsible for more than 85% of the variation in CP content across the mixtures. Although clovers did not appear to significantly affect total biomass yield, their inclusion plays a critical role in improving forage nutritional value, making them a valuable component for livestock feed.

5.2 Potential effects of grazing cattle on the environment

Environmental effects of cattle production are significant and include water pollution, land degradation, and greenhouse gas emissions. About 10% of emissions worldwide are methane from enteric fermentation and animal manure management (Steinfeld et al., 2006). The spread of pasture and feed crops is also the primary cause of deforestation in areas like Latin America, where grazing occupies about 30% of the planet's land area (Carrell, 2022; Reiter et al., 2024). Cattle are important both culturally and economically, yet their production poses major environmental issues that demand international attention (Kass, 2024). Trampling produced very dense zones at depths of 7–10.5 cm, which impeded drainage, despite the presence of large

macropores. Soil structural and hydrological changes caused by hoof compaction can result in serious pasture management problems (Mulholland & et al.,1991).

Cover crop grazing may affect the physical characteristics of the soil and can reduce compaction. Recent research, however, confirms that when soil compaction effects do occur, they are limited to the top 10 cm of the soil and have little bearing on the ability of subsequent cash crops and CC to develop roots and produce (Franzluebbers and Stuedemann, 2008a; Balbinot Jr et al., 2011; Kelly et al., 2021). When grazed and ungrazed CC were compared to fallow soil, Kelly et al. (2021) observed that the use of CC improved soil aggregate stability whereas cattle grazing had no effect on soil compaction. Compared to ungrazed fields, grazed and fallow fields had higher bulk densities.

Balbinot Jr. et al. (2011) evaluated the impacts of grazing cool-season annual CC with and without N fertilization in comparison to volunteer vegetation, seed-oil brassica CC, and an ungrazed mixed sward CC compared to the grazing treatment that included N. This study discovered that grazing enhanced soil compaction in the top layer of subsoil (0–5 cm) in the grazing treatment that lacked N. This suggests that the forage production was less, and that trampling was greater. Since there is no difference in the lower subsurface zones, grazing with cattle would not prevent the root growth of future cash or CC.

Despite all these possible impacts, ruminant animals like cattle contribute to the maintenance of healthy soils and grasslands, and proper grazing management can reduce the industry's C emissions and overall footprint. While conserving the protective properties of the CC as originally intended, ruminant animal grazing promotes quick nutrient recycling (Franzluebbers, 2007). The health and microbiological activity of soil can be greatly improved by storing SOM, especially organic C (Poffenbarger, 2010). Grazing livestock could be seen as a component of

the answer to preserve existing land conditions and lower greenhouse gas emissions. According to (Soussana et al., 2010), sequestration of C from the atmosphere into soils also helps reduce environmental concerns related to excess CO₂ produced by microbial fermentation in grazing livestock. Nutrient recycling will be decreased if plant biomass increase from grazing is decreased, according to anecdotes. Over a four-year period, however, studies have demonstrated that a crop rotation consisting of corn and grazed oats accumulated 2–4% more organic C than all cropping systems, except for perennial cool-season pastures (Tracy and Zhang, 2008). The use of grazed or ungrazed CC has been shown to improve N use efficiency by 12 to 15%, making it another crucial soil and plant nutrient (Franzluebbers, 2007).

Chapter II. Grazing cover crops: effect on animal and cover crop performance

1. Introduction

Monoculture agriculture and the absence of year-round vegetative cover have been linked to cascading environmental externalities—including elevated pest pressure, fertilizer runoff, higher disease incidence, and the spread of herbicide-resistant weeds—which collectively erode land productivity over time (Environmental Literacy Council, 2025). Accordingly, enhancing plant diversity within cropping systems has emerged as a practical, system-level strategy to interrupt pest and pathogen cycles, improve nutrient retention, and sustain productive capacity. Using multispecies cc in the fallow season is one method of promoting plant diversity (Pereira et al., 2023).

Cover crops not only minimize soil erosion (Langdale et al., 1991), but they also reduce nutrient loss and runoff (Li et al., 2006), enhance soil fertility (Cavigelli and Thien, 2003), and decrease weed and insect encroachment (Creamer and Baldwin, 2000). Despite their many environmental benefits, CC have not been widely adopted, primarily due to their slow economic return on investment. According to Pereira et al. (2023), the overall health and structure of agricultural land soils are significantly improved by these outcomes of several plant-soil interactions. They are planted during the cash crops' off-season with the intention of supporting the subsequent cash crop. Common forage crops that are highly yielding for a brief period and offer one or more ecological advantages to the soil profile are frequently used as cc.

A reduction in the amount of land available for raising livestock and food crops is likely to correspond with an increase in demand for food and other agricultural products. Increased

production efficiency is required when land becomes less available. According to Franzluebbbers (2007), crop livestock systems have the potential to fulfill two functions: they can maintain or improve the surrounding agroecosystem and provide a sustainable food supply using fewer land resources, while also producing agricultural products during periods when crops are not growing.

To provide ecosystem services, CC need to produce adequate aboveground biomass to shield soil from weather-related disasters like drought or rain. Animals, like beef cattle, may be able to use plant biomass as a grazing crop. Although they can be annual grasses, legumes (clovers), or forbs (brassicas), CC frequently combine these three forage families. Utilizing these species in a cc mixture enhances the beneficial effects of the cc on the ecosystem and soil (Pereira et al., 2023).

Crop and livestock system integration can be a useful management approach which allows the combination of two industries that complement one another. In the Southeast, stocker cattle production frequently employs these forages. Grazing cool-season annuals can benefit stocker cattle growth and overall output per land unit in the systems, according to several Southeast researchers trials in integrated systems (Beck et al., 2014; Mullenix et al., 2014; Marchant et al., 2019). Grazing CC has a negligible effect on the yields of subsequent cash crops (Balbinot Junior et al., 2011; Kelly et al., 2021) or soil quality parameters like bulk density, water holding capacity, nitrogen cycling, and soil organic matter (SOM) in the Southeast (Franzluebbbers and Steudemann, 2008a; Tracy and Zhang, 2008). Grazing management recommendations for multi-species cover crops remain unclear. Although these forages may serve as effective grazing option, their response to grazing pressure and impact on beef production is not well understood. It is also uncertain whether continuous stocking affects their ability to regenerate and provide ecosystem benefits. This study aimed to evaluate forage yield and animal performance of grazed

and ungrazed cool-season annual CC in a cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea* L.) rotation in southern Alabama.

2. Materials and methods

2.1 Research site

All procedures for this experiment were approved by the Auburn University Institutional Animal Care and Use Committee (IACUC; Protocol #2021-3997 and #2024-5505). A 2-yr grazing experiment was conducted at the Wiregrass Research and Extension Center (Headland, AL; 31.35° N, 85.34° W). Twelve paddocks (0.6 ha each) were established on Dothan fine sandy loam (Fine-loamy, kaolinitic, Plinthic Kandiudults). In the summer preceding Year 1 (2023), paddocks were planted to annual peanut (*Arachis hypogaea* L.) as part of a cotton (*Gossypium hirsutum* L.)–peanut rotation. Cotton followed grazing after Year 1 (2023), and annual peanut followed grazing after Year 2 (2024). Composite soil samples (0–15 cm; thoroughly mixed) were collected on 3 December 2023 and 22 November 2024 to characterize initial site conditions prior to cover-crop establishment.

Figures 1 and 2 represent the temperature and precipitation data collected for the period from October 2022 to April 2024. Figure 1 shows the monthly temperature averages for each year (2022–2024), compared to the 30-year mean (1992–2021) obtained from the NASA POWER dataset. The 30-year mean temperature for each month was calculated based on historical data from 1992 to 2021, serving as a reference for comparison with the recent years. Similarly, Figure 2 illustrates the monthly precipitation values for the same period (October 2022–April 2024), with a comparison to the 30-year mean precipitation for each month, also based on data from the NASA POWER dataset. Both figures highlight the differences between

the recent data and historical averages, providing context for the seasonal climate variations during the study period.

2.2 Paddock Establishment and Fertilization

Each year, paddocks were planted with a one-, two-, or three-species winter cover-crop mixture representing brassica grass only treatment, a grass-legume treatment, and a grass-legume-brassica treatment. The mixture consisted of oat ('Coker' oat; *Avena sativa* L.; grass), crimson clover ('Dixie'; *Trifolium incarnatum* L.; legume), and a forage brassica ('Purple top' turnip *Brassica rapa* L.). Species composition of the mixture was identical in both years. Seeding was performed with a no-till drill (Great Plains Mfg., Salina, KS) on 20 November 2022 (Year 1) and 9 November 2023 (Year 2) using 19-cm row spacing. Target seeding rates were oat only, 101 kg pure live seed (PLS)/ha; oat + clover, 101 kg PLS/ha oat and 9 kg PLS/ha clover; oat + clover + brassica, 101 kg PLS/ha oat, 9 kg PLS/ha clover, and 3.4 kg PLS/ha brassica. Depth targets were 2.5 cm for oat and 1.25 cm for clover and brassica.

In both years, grazing paddocks received 60 kg N/ha as ammonium sulfate $(\text{NH}_4)_2\text{SO}_4$ in December, approximately 3–5 weeks prior to grazing initiation in January. Phosphorus and potassium were applied only when indicated by soil test sufficiency thresholds. At the end of each grazing season, cover crops were terminated according to standard extension recommendations (chemical desiccation timed to the succeeding summer crop), and summer cash crops (cotton or peanut, per rotation) were established following routine producer practices for tillage and planting (Reiter et al., 2024).

2.3 Experimental Design

The study was structured as a randomized complete block design with two grazing treatments and three forage treatments in three replicated paddocks per treatment each year. Grazing

treatments were: (1) no grazing (NG) and (2) grazed (G). Forage treatments were: (1) oat; (2) oat+clover; and (3) oat+clover+turnip. Grazed paddocks were 0.6 ha. Non-grazed controls were maintained as 0.2-ha ungrazed areas of the same species composition and planting dates, managed identically except for the absence of cattle. Blocking accounted for spatial field variability across the paddock array.

2.4 Animal and Forage Management

Each year, 55 Angus-crossbred steers were received and maintained on ad libitum bermudagrass hay (*Cynodon dactylon* L.) for ~60 d prior to grazing. Before allocation, steers were individually identified, dewormed with a pour-on macrocyclic lactone (Cydectin®, Boehringer Ingelheim, Ridgefield, CT), and implanted (Ralgro®, Merck Animal Health Intervet Inc., Madison, NJ). Animals had continuous access to a commercial mineral/salt mix (Mag Plus Beef Mineral/Salt, Southern States Cooperative Inc., Richmond, VA) and fresh water. Grazing began each January of each year and terminated in March-April once mean forage biomass exceeded 1,000 kg DM/ha across paddocks (Table 1). Three tester steers (8 mo of age; initial body weight [BW] 266 ± 18 kg) were randomly allocated to each grazed paddock in both years.

Tester steers were used to determine initial BW, final BW, and average daily gain (ADG). Stocking adjustments followed the put-and-take method originally described by Mott and Lucas (1952), with biweekly adjustments to maintain a forage allowance of 1 kg DM per kg BW, implemented as in contemporary protocols (e.g., Sollenberger & Burns, 2001; Marchant et al., 2019; Mullenix et al., 2014). All steers assigned to grazing were weighed immediately prior to turn-in and at removal at the end of the grazing period. Grazing concluded in late spring each year when forage allowance could no longer support the three continuously stocked tester steers.

During the two-year study, no additional put-and-take steers were used therefore the stocking rate was 5 hd/ha throughout the study.

3. Forage Sampling and Laboratory Analyses

Forage was sampled immediately prior to grazing initiation and every 14 d thereafter. Within each paddock, four biomass samples and two botanical-composition samples were collected on each date and mixed back together. Samples were clipped to ~5 cm stubble height within a 0.5-m² quadrat using battery-powered shears, placed into cloth bags, and transported to the Ruminant Nutrition Laboratory (Auburn University, Auburn, AL).

Biomass samples were dried at 55 °C in a forced-air oven for 48–72 h until constant mass was reached, air-equilibrated, and weighed to estimate dry-matter (DM) yield. Botanical-composition samples were separated upon arrival into grass, clover, brassica, and weeds; fractions were dried under the same conditions, air-equilibrated, weighed, and expressed as a percentage of total sample mass.

Dried forage was ground in a Wiley Mill (Thomas Scientific, Swedesboro, NJ) to pass a 2-mm screen. Crude protein and DM were analyzed according to AOAC methods (AOAC International, year per lab SOP). Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were determined using a detergent-fiber procedure validated for forage analysis (Vogel et al., 1999/ANKOM-based method). Forage allowance (FA) was calculated at each sampling date as available forage dry matter per unit of live animal weight on an area basis, (Rouquette et al., 2016). FA was expressed as kilograms of dry matter (DM) per kilogram of body weight (BW) per hectare:

$$FA = \frac{\text{Available forage } \left(\frac{\text{kg DM}}{\text{ha}} \right)}{\text{Total live BW } \left(\frac{\text{kg}}{\text{ha}} \right)}$$

3.1 Soil Sampling and Analyses

At the end of grazing trial, composite soil samples (10–15 cm depth) were collected to characterize soil chemical status. Composites were analyzed for soil organic matter (SOM), and Mehlich-3 extractable nutrients (P and k) and for N at the Soils Lab in Auburn University using standard methods (e.g., Sikora et al., 2014; Nelson and Sommers, 1996). Soil results informed in-season fertility only when values fell below sufficiency ranges.

4. Statistical analysis

Data were analyzed in SAS 9.4 (SAS Institute Inc., Cary, NC). Distributions were screened with PROC UNIVARIATE (NORMAL). All models used PROC GLIMMIX with Kenward–Roger denominator degrees of freedom. Paddock (within year) was the experimental unit. Least-squares means (LS-means) were compared with Tukey–Kramer adjustment; significance was set at $\alpha = 0.05$.

4.1 Forage

Forage biomass (kg DM/ha) and nutritive value (CP, NDF, ADF) were analyzed with fixed effects of grazing (non-grazed, NG; grazed, G), forage composition (oat; oat+clover; oat+clover+brassica), year (2023, 2024), and their interactions. Paddock within year was specified as a random effect and sampling date was a repeated measure. Significance was determined at $P \leq 0.05$.

4.2 Animal variables

Animal responses (initial BW, final BW, ADG, gain per hectare, forage allowance, stocking

density, grazing days) were analyzed with fixed effects of forage treatment (grass only; grass + legume; grass+legume+brassica) and year. Paddock within year was the random effect. Non-grazed paddocks were excluded from animal-performance and forage-allowance analyses by design. Significance was determined at $P \leq 0.05$.

4.3 Soil

Soil variables (Mehlich-3 nutrients) were analyzed using repeated measures of sampling date with paddock within year as a random effect and fixed effects of grazing, forage composition, year, and their interactions. Significance was determined at $P \leq 0.05$.

5. Results and Discussion

5.1 Botanical composition

Averaged across the season, forage treatment shifted all botanical groups in expected directions. Grass was highest in O, intermediate in O+C, and lowest in O+C+T ($P < 0.01$), while weeds were greatest in O and reduced in mixtures ($P = 0.02$; O vs. O+C and O vs. O+C+T both $P = 0.02$). For clover, forage treatment was significant ($P < 0.01$) and a forage treatment \times grazing management interaction occurred ($P = 0.01$): O+C and O+C+T exceeded O (both $P < 0.001$), with small NG–G shifts that did not change the ranking. Brassicas appeared only in O+C+B (~8.3%) and were treatment-driven ($P < 0.001$) with no grazing management effect ($P = 0.92$).

By contrast, the grazing management system (NG vs. G) defined here as short-term winter grazing within a single cool-season window (Jan–Mar) under moderate stocking, put-and-take targeting forage allowance ~1 kg DM per kg BW with biweekly adjustments did not alter grass ($P = 0.60$) or weed ($P = 0.75$) shares and only modulated clover slightly via the interaction.

These patterns are consistent with the idea that adding functional groups can reduce grass dominance via competition and niche partitioning (Williams & Weil, 2004) and enhance weed suppression through resource capture (Wortman et al., 2012; Osipitan et al., 2019), while cereals and legumes commonly persist under managed winter grazing in the Southeast when forage allowance is maintained (Franzluebbbers & Stuedemann, 2008; Carrell, 2022); Comparable botanical outcomes have been reported by Tracy and Zhang (2008) and Beck et al. (2005), who found that moderate winter grazing did not reduce legume persistence or alter the grass–legume balance when forage allowance was maintained. Similarly, Finney and Kaye (2017) observed

that species complementarity in mixtures can reduce weed abundance and shift canopy structure toward more even functional group representation.

In a meta-analysis of cover crop systems, (Florence et al., 2019) also reported that species diversity improved weed suppression but did not always increase total legume proportion, aligning with our modest shifts in clover percentage. As shown in (Table 2), the addition of brassicas in mixtures contributed to a minor increase in the proportion of brassicas, but no significant effect on the overall botanical composition was observed. At the same time, syntheses note that mixtures do not universally outperform well-chosen monocultures for every function, emphasizing context and management (Smith et al., 2020).

6. Forage yield

Total forage yield did not differ by forage treatment (O, O+C, O+C+B; $P = 0.83$), grazing management system (NG vs. G; $P = 0.42$), or their interaction ($P = 0.14$) as shown in (Table 3). Treatment LS-means fell within 1.3–1.5 Mg DM/ha (~ 1,300–1,550 kg DM/ha), so we refrain from interpreting numerical ordering in the absence of statistical support. Comparable results were reported by Beck et al., 2005) and (Myer et al., 2008), who observed no significant biomass differences among cool-season annual mixtures in the southeastern U.S. despite numerical trends favoring oats. These results indicate that, within a short winter window, multispecies mixtures did not produce greater biomass than oat monoculture consistent with reviews showing that biomass advantages from mixtures are context dependent (environment, growth duration, and species complementarity) rather than guaranteed (Blanco-Canqui, 2015; Florence et al., 2019; Smith et al., 2020). Finney and Kaye (2017) and Ranaldo et al. (2020) similarly found that yield benefits from mixtures emerge mainly under longer growth periods or when environmental resources (nutrients, moisture) are limiting, supporting the limited response observed here.

Importantly, the management system did not reduce standing biomass during our sampling period, aligning with reports that short-term, well-managed winter removal can be integrated without depressing cover-crop biomass during the period of use (Tracy & Zhang, 2008) and, in many systems, without penalizing subsequent cash-crop performance when residue and timing are managed (Kuhn, 2021). Comparable findings from (Boniface et al., 2024) and Finney et al. (2016) indicate that moderate grazing intensity or biomass removal events often maintain similar end-of-season yields as ungrazed controls, emphasizing management over species composition. Taken together, our findings suggest that forage yield alone may not justify mixture costs unless accompanied by other agronomic benefits (weed suppression or soil functions) documented (Blanco-Canqui, 2015; Smith et al., 2020; Ranaldo et al., 2020).

7. Nutritive value

Across the two-year period, forage treatment (O, O+C, O+C+B) did not affect CP ($P = 0.66$), NDF ($P = 0.97$), or ADF ($P = 0.37$), and no treatment \times grazing management interactions were detected for these variables ($P > 0.45$). By contrast, the grazing management system (NG vs. G) reduced NDF ($P = 0.05$), while CP ($P = 0.73$) and ADF ($P = 0.30$) were unchanged as shown in (Table 3). Least squares mean fell within typical ranges for oat-based winter mixtures in the Southeast (CP 16–17%, NDF 50–51%, ADF 30–32%), consistent with previously reported values for oat/rye mixtures with crimson clover or brassica (Phillips et al., 2019). Because final biomass is treated separately, the interpretation here focuses on chemical composition rather than quantity.

Given that botanical composition averaged across the season showed grasses dominating O and remaining substantial in O+C and O+C+T, the lack of treatment effects on CP/NDF/ADF is expected: when the grass fraction governs canopy mass, legume/brassica effects

on bulk forage chemistry are often muted (Bracey et al., 2022; Carrell, 2022). The NDF decrease under the G management system ($P = 0.05$) aligns with reports that timely winter defoliation can maintain a more vegetative sward state (earlier phenology at sampling) and limit fiber accumulation without depressing protein (Tracy & Zhang, 2008; Phillips et al., 2019). We did not measure leaf: stem ratio; thus, we attribute the NDF response to phenological/structural status as supported by the literature rather than to a measured morphological change in our dataset.

Despite the inclusion of brassica in O+C+B, ADF did not differ among treatments ($P = 0.37$). This agrees with studies showing that brassicas introduced at moderate proportions operationally, <10% of the sward by canopy share in our trial (8.3%) do not impair fiber fractions or digestibility when grazing is timely (Bracey et al., 2022). From a nutritional standpoint, the NV achieved here is adequate for stocker cattle: CP near 16–17% meets or exceeds requirements for ~260–300 kg steers targeting ≥ 1.0 kg/d gains, while NDF 50% is compatible with high intake potential under sufficient allowance [NRC, 2016; Mertens, 1994; Moore & Jung, 2001]. Together, these results indicate that mixture composition did not materially alter forage chemistry under our short winter window, whereas management timing can modestly fine-tune NDF within an already high-quality baseline.

8. BW, ADG and BW gain per area

8.1 Initial and final BW

Initial BW did not differ among grazed treatments ($P = 0.94$), and final BW was likewise not different ($P = 0.76$), indicating balanced allocation and consistent preconditioning across paddocks as shown in (Table 4).

8.2 Average daily gain

Average daily gain did not differ by forage treatment ($P = 0.42$) As shown in (Table 4). In absolute terms, winter annual systems commonly support stocker gains around 1.0–1.2 kg/d under typical management, with higher gains when planting is early, forage allowance is adequate, or conditions are especially favorable. For example, steers on early-planted wheat achieved 1.02–1.21 kg/d vs. 0.81–0.98 kg/d on late-planted wheat (Oklahoma; multi-year) (Fieser et al., 2006), and management reviews for wheat pasture corroborate that system and timing govern performance variability (Horn, 2006). More broadly across cool-season forages, cultivar/species choices and management nuances can shift performance but do not guarantee treatment effects each year (Beck et al., 2005; Scaglia et al., 2021). For example, (Myer et al., 2008) and (McKee et al., 2017) compared the performance of different cool-season mixtures and found that although species choice influenced ADG, management practices like stocking density and grazing period length were more critical to overall performance.

8.3 Gain per hectare

Total live-weight gain per hectare showed no forage treatment effect ($P = 0.70$) as shown in (Table 4). Reported benchmarks for cool-season systems span a wide range, from roughly 200–300 kg/ha in shorter grazing windows to >500 kg/ha with longer seasons or higher stocking rates, provided forage quality and allowance are sustained. Multi-treatment comparisons in Arkansas, for instance, found no across-year differences in gain/ha among several cool-season options, illustrating the role of year effects and management in land-area productivity (Beck et al., 2005). Similar findings by (McKee et al., 2017) and (Mullenix et al., 2012) showed no significant differences in gain per hectare among several cool-season forage treatments,

suggesting that year-to-year environmental conditions often have a stronger effect on productivity than forage composition itself. Likewise, studies in rye/annual-ryegrass systems and regional syntheses emphasize that gain per hectare is highly contingent on season length, stocking rate, and tactical decisions. (Butler et al., 2012), (Dillard et al., 2018), and (OSU Extension, 2017) emphasize that when forage quality is managed appropriately, the key factors affecting gain per hectare are season length, stocking density, and management decisions, rather than the specific forage mixture used.

Taken together, adding clover and brassica did not statistically alter ADG or gain/ha under our short winter window with put-and-take adjustments, which aligns with literature showing that improvements typically emerge when there are longer grazing periods, distinct stocking levels/allowances, or clearer quality contrasts conditions that vary by year and system (Horn, 2006; Beck et al., 2005; Fieser et al., 2006; Butler et al., 2012).

9. Soil composition and nutrients

9.1 Organic matter

This study continues prior work at the site (Carrell, 2022) and interprets responses relative to the baseline soil tests described in Methods (0–15 cm; 22 Nov 2023 and 22 Nov 2024). Across both years, soil organic matter (SOM) was not affected by cover-crop treatment or management system ($P \geq 0.05$) as shown in (Table 5). This outcome aligns with evidence that SOM changes require multiple seasons and are driven more by residue retention and tillage intensity than short-term shifts in species composition (Blanco-Canqui & Lal, 2008; Poeplau & Don, 2015; Lucas & Weil, 2012); in grazed cover-crop systems, detectable soil-C responses also tend to occur over longer time frames or under more contrasting grazing regimes (Franzluebbers, 2010).

9.2 Nitrogen

Soil N was not influenced by treatment or year overall ($P \geq 0.05$); however, a forage treatment \times year \times grazing management interaction was detected ($P = 0.01$) as shown in (Table 6), indicating that N responses depended jointly on seasonal conditions and whether paddocks were non-grazed or grazed. This dependence is consistent with functional mechanisms in mixtures, legumes can enhance N inputs and retention when biomass remains on site and disturbance is minimized (Dabney et al., 2001; Tonitto et al., 2006), functional diversity can improve N capture and cycling (Finney et al., 2016), and management governs the pathway and timing of N return to soil (White et al., 2016). Accordingly, inference should emphasize simple effects within year and management rather than main-effect averages.

9.3 Phosphorus

Soil P did not vary by forage treatment, grazing management system, or year ($P \geq 0.05$) as shown in (Table 7). Mechanistically, several plant functional groups can influence P cycling over longer durations, legumes by stimulating P-solubilizing microbes and phosphatase activity (Richardson et al., 2009), grasses by supplying rhizosphere carbon that fuels microbial turnover (Stutter et al., 2012), and some brassicas by exuding organic acids that may increase labile P where soil chemistry permits (Menezes-Blackburn et al., 2018) but realized shifts in soil-test P typically require extended management (Finney et al., 2016).

9.4 Potassium

In contrast to SOM, N, and P, soil K showed significant main effects of forage treatment ($P = 0.01$) and grazing management system ($P = 0.04$), with no forage treatment \times grazing management interaction as shown in (Table 8). On average, K was greater in the oat+clover+brassica mixture than in other treatments, consistent with reports that certain

broadleaf cover crops mobilize and retain exchangeable near the surface via high tissue uptake and cycling (Sattell et al., 1998; Whitehead, 2000; Kumar et al., 2022). K was also greater under non-grazed than grazed conditions, aligning with evidence that grazing can export or redistribute K through biomass removal and off-paddock deposition (Whitehead, 2000; Maughan et al., 2009).

Table 1. Grazing initiation and termination dates for cover crops (grass, legume, and brassica) grazed with yearling steers at the Wiregrass Research and Extension Center (Headland, AL).

Year	Grazing initiation	Grazing termination	Length of season, d¹
2023	January 13	March 22	69
2024	February 2	April 18	76

¹Dates represent initiation and termination of grazing periods for yearling steers in multispecies cover crops.

Table 2. Percent botanical composition (%DM) of grass, legume, brassica and weed in mixtures.

Item	Oat	Oat+Clover	Oat+Clover+Brassica	Mean	SEM1	P-value)
Grass, % ²	83.6 ^a	76.4 ^b	71.0 ^c	77.0	0.60	< 0.01
Clover, % ²	0.2 ^c	16.1 ^a	13.5 ^b	14.8	0.64	< 0.01
Brassica, %	0.0 ^b	0.0 ^b	8.3 ^a	2.8	0.54	< 0.01
Weed, % ²	15.1 ^a	7.6 ^b	7.6 ^b	10.1	0.52	0.02

¹SEM = standard error of the mean.

²Within a row, means without a common superscript differ ($P < 0.05$).

(Different superscripts within a row indicate LS-mean differences at $\alpha = 0.05$; P-values shown are for the fixed effect of Treatment.)

Table 3. Forage yield (kg Dm/ha) and nutritive value (%DM) of grass, grass+legume, and grass+legume+brassica paddocks grazed by yearling steers at the Wiregrass Research and Extension Center (Headland, AL).

Item	Oat	Oat+Clover	Oat+Clover+Brassica	Mean	SEM²
Forage Yield, kg DM/ha	1314	1443	1534	1431	435.5
CP¹, %	16.6	17.0	16.7	16.8	0.48
NDF, %	51.1	50.8	51.0	51.0	1.40
ADF, %	30.6	30.7	32.1	31.1	0.83

¹CP = crude protein; NDF = neutral detergent fiber; ADF = acid detergent fiber.

²Standard error of the mean.

Table 4. Initial body weight (BW; kg), final body weight (BW; kg), average daily gain (ADG; kg/d), and total body weight gain per hectare of steers grazing cover crops of grass, grass+legume, or grass+legume+brassica at the Wiregrass Research and Extension Center (Headland, AL).

Item	Oat	Oat+Clover	Oat+Clover+Brassica	Mean	SEM¹
Initial BW, kg	265	266	267	266	11.4
Final BW, kg	356	361	361	359	14.5
ADG, kg	1.3	1.36	1.31	1.31	0.47
BW gain/ha, kg	206	204	211	212	26.1

¹SEM = standard error of the mean.

Table 5. Soil organic matter concentration (%) in soil under nongrazed or grazed cover crops grazed by yearling steers at the Wiregrass Research and Extension Center (Headland, AL).

Year	Grazing	Oat	Oat+Clover	Oat+Clover+Brassica	Mean	SEM²
2023	NG	2.31	2.34	2.30	2.32	0.31
	G	2.32	2.28	2.22	2.27	0.31
2024	NG	2.58	2.35	2.34	2.42	0.31
	G	2.22	2.48	2.31	2.34	0.31

¹NG = not grazed; G = grazed.

²Standard error of the mean.

Table 6. Soil nitrogen (ppm) concentration under nongrazed or grazed cover crops by yearling steers at the Wiregrass Research and Extension Center (Headland, AL).

Year	Grazing¹	Oat	Oat+Clover	Oat+Clover+Brassica	Mean	SEM²
2023	NG	0.055 ^b	0.053 ^b	0.052 ^b	0.053 ^b	70
	G	0.039 ^c	0.048 ^b	0.046 ^b	0.044 ^c	70
2024	NG	0.057 ^b	0.056 ^b	0.065 ^a	0.059 ^a	70
	G	0.066 ^a	0.050 ^b	0.049 ^b	0.055 ^a	70

¹NG = not grazed; G = grazed.

² SEM = standard error of the LS-mean for treatment comparisons within the given Year × Grazing stratum (SAS GLIMMIX LS-means SE ≈ 70 mg kg⁻¹, equivalent to 0.007%).

Table 7. Soil phosphorus (ppm) concentration under grass, grass+legume, and grass+legume+brassica cover crops grazed by yearling steers at the Wiregrass Research and Extension Center (Headland, AL).

Year	Grazing¹	Oat	Oat+Clover	Oat+Clover+Brassica	Mean	SEM²
2023	NG	21.30	20.50	20.80	20.87	4.66
	G	20.60	20.80	21.10	20.83	4.66
2024	NG	22.23	22.17	20.90	21.77	4.66
	G	21.10	21.67	21.10	21.29	4.66

¹NG = not grazed; G = grazed.

²Standard error of the mean.

Table 8. Soil potassium (ppm) concentration under grass, grass+legume, and grass+legume+brassica cover crops grazed by yearling steers at the Wiregrass Research and Extension Center (Headland, AL).

Year	Grazing¹	Oat	Oat+Clover	Oat+Clover+Brassica	Mean	SEM²
2023	NG	91.7	82.4	80.5	84.87	17.40
	G	89.0	83.5	79.3	83.93	17.40
2024	NG	84.5	79.0	60.1	74.53	17.40
	G	80.0	76.4	62.2	72.87	17.40

¹NG = not grazed; G = grazed.

²Standard error of the mean.

Figure 1. Total monthly temperature and 30-yr mean temperatures for October through April at the Wiregrass Research and Extension Center, Headland, Al; Year 1, 2022-2023; Year 2, 2023-2024.

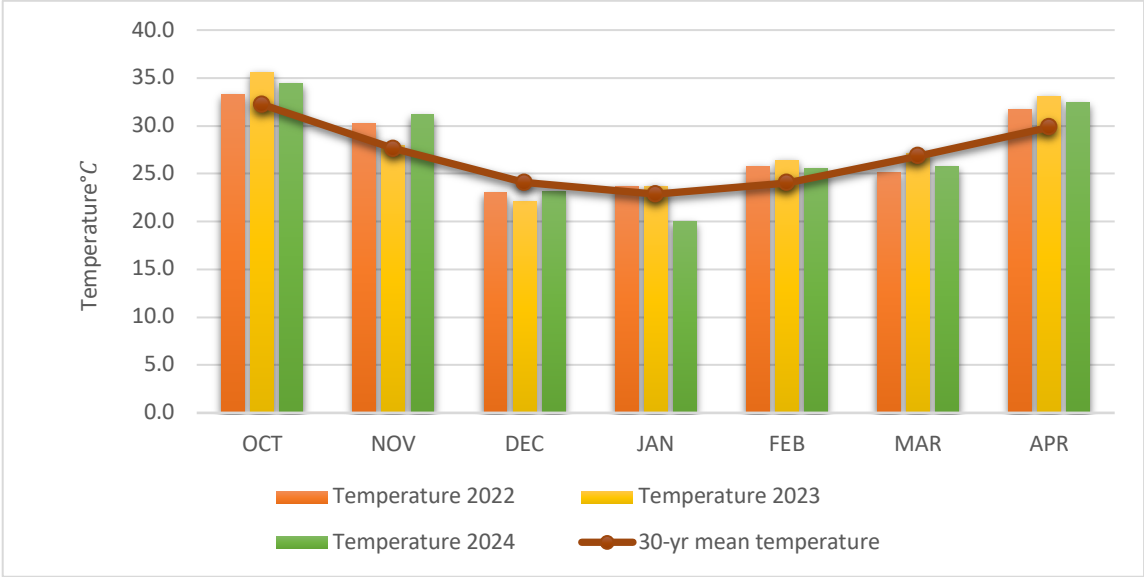
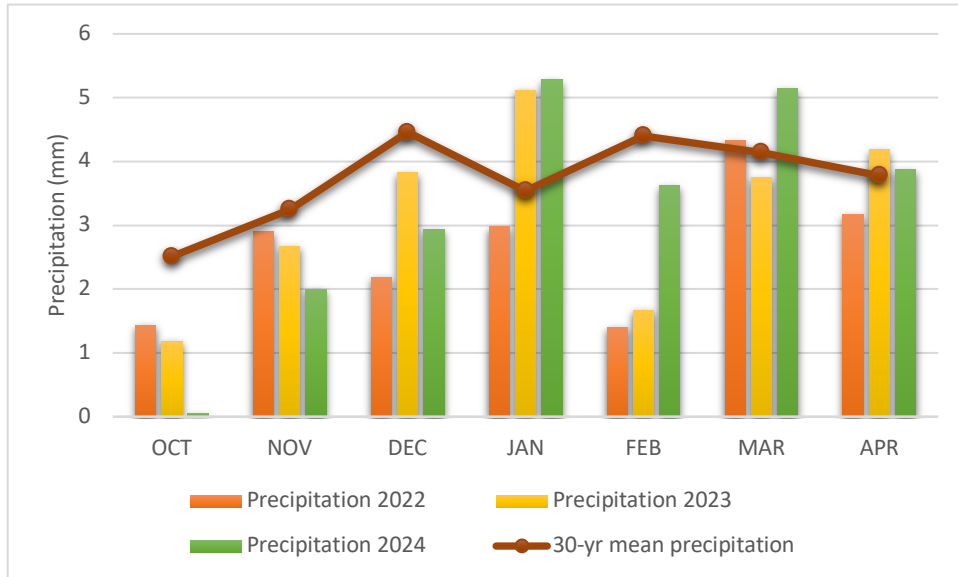


Figure 2. Total monthly precipitation and 30-yr mean precipitations for October through April at the Wiregrass Research and Extension Center, Headland, Al, Year 1, 2022-2023; Year 2, 2023-2024.



Conclusions

The integration of multispecies cool-season cover crops into cotton–peanut rotations demonstrate strong potential as a sustainable practice for enhancing winter forage availability while maintaining soil health in the southeastern United States. Over two years of evaluation, moderate grazing did not reduce total forage yield or negatively impact soil organic matter, phosphorus, or nitrogen content. As shown in Table 5, soil organic matter remained stable, in line with findings from previous studies indicating that significant SOM changes typically require multiple seasons and are more driven by residue retention and tillage intensity rather than short-term shifts in species composition (Blanco-Canqui & Lal, 2008; Poeplau & Don, 2015; Lucas & Weil, 2012). Notably, potassium levels were influenced by both grazing and species composition, with higher K retention observed in non-grazed paddocks containing brassica mixtures. These findings are consistent with reports that broadleaf crops, such as brassicas, can mobilize and retain exchangeable K near the surface through high tissue uptake and cycling (Sattell et al., 1998; Whitehead, 2000; Kumar et al., 2022).

Botanical composition data confirmed that the inclusion of clover and brassica suppressed weed incidence, likely through increased canopy density and competitive exclusion. This result aligns with studies by Wortman et al. (2012) and Osipitan et al. (2019), which observed that diverse functional groups in cover crops can effectively suppress weeds through improved resource capture and niche partitioning. Although no significant improvements in crude protein or forage biomass were observed due to species inclusion, grazing contributed to lower NDF concentrations, indicating enhanced forage digestibility under defoliation pressure. Similar

results were reported by Tracy & Zhang (2008), who found that timely winter defoliation helps limit fiber accumulation in mixed-species systems without negatively affecting protein content.

Steer performance, measured through initial and final BW, ADG, and gain per hectare, was not significantly affected by the duration of grazing, with ADG averaging 1.2 kg/day and BW gain per hectare ranging from 388 to 466 kg/ha. These results suggest that traditional stocking densities may not fully utilize the potential of cover crops for sustained cattle gain, especially in systems managed with fixed grazing windows. Comparable results were reported by Beck et al. (2005) and Fieser et al. (2006), who observed that stocker gains often depend on appropriate management timing and grazing duration rather than on forage species alone.

Overall, grazing multispecies cover crops can be implemented without detriment to soil nutrient status or subsequent crop productivity. However, to fully capitalize on their multifunctionality, future research should evaluate adaptive grazing strategies such as grazing to specific residual heights, adjusting seeding rates, or manipulating species combinations to enhance both forage use efficiency and conservation outcomes in integrated crop–livestock systems. These findings align with recommendations from Ranaldo et al. (2020) and Finney & Kaye (2017), who emphasized the importance of adapting grazing strategies to maximize both forage and environmental benefits in mixed-crop systems.

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