Cover Crop Management Practices to Improve Soil Health and Weed Suppression in Cropping Systems

by

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Abstract

Introducing integrated crop-livestock systems into row crop production may provide incentives for producers to plant cover crops and promote soil health benefits on degraded soils of the southeastern United States, but effects of these practices on crop yields and soil health in coastal plain soils are not well established. A four-year study was established at the Wiregrass Research and Extension Center in Headland, Alabama to test the effects of different grazing regimes on soil health and crop productivity. Three cattle grazing regimes (mid-February, mid-March, and mid-April cattle removal dates) and an non-grazed control were included in a randomized complete block design and replicated three times. Chemical soil health indicators (soil organic carbon, permanganate oxidizable carbon), physical soil health indicators (water stable aggregates, penetration resistance), biological soil health indicators (microbial biomass carbon, arbuscular mycorrhizal fungi colonization), crop yield, and cover crop biomass were evaluated. Cover crop biomass at termination was reduced for all grazed treatments compared to the non-grazed control, and the mid-March and mid-April treatments resulted in the lowest amount of cover crop biomass. No treatment effects were observed for arbuscular mycorrhizal fungi, microbial biomass carbon, and permanganate oxidizable carbon. Soil organic carbon was higher in the non-grazed treatment than the mid-April grazing treatment for the 0-30 cm depth. Penetration resistance at the 0-50 cm depth and water stable aggregates at the 0-30 cm depth were both negatively impacted by increased grazing period lengths. Results from this study suggest that longer cover crop grazing periods have little effect on biological and chemical soil health indicators in the short term but can negatively impact some physical soil health indicators.

Shorter grazing periods allowed for regrowth of cover crop biomass, leaving more residues to prevent soil erosion and reduce soil compaction.

Control of herbicide resistant weeds is a growing problem for southeastern row crop producers. Utilizing alternative programs that integrate winter cover crops with postemergence herbicides may be an effective form of weed management. Field studies were conducted at the Tennessee Valley Research and Extension Center in Belle Mina, AL in 2022 and 2023 and at the E.V. Smith Research Center in Shorter, AL in 2023. An experiment using a 2x2x3 factorial design with 4 replications was used to evaluate the ability of different cover crop management practices in conjunction with preemergence herbicides for weed suppression in soybeans (*Glycine max*). Main factors were two seeding rates of a cereal rye + crimson clover mixture, two cover crop nitrogen fertilization rates, and three preemergence herbicide treatments (untreated, S-metolachlor, acetochlor) applied to soybeans at planting. Cover crop biomass was collected to observe the effects of seeding and fertilization rates on aboveground biomass production. Weed counts were conducted ~14, 28, 42, and 56 days after soybean emergence in two, 1 m^2 areas within each plot. Common weed species observed were large crabgrass (*Digitaria sanguinalis*), Palmer amaranth (*Amaranthus palmeri*), prickly sida (*Sida spinosa*), barnyardgrass (*Echinochloa crus-galli*) and morningglories (*Ipomoea* spp.). Cover crop biomass (P=<0.0001), herbicide treatment (P=<0.0001) and herbicide x time interaction (P=<0.0001) all had a significant effect on weed emergence. Weed emergence was lower for the S-metolachlor and acetochlor treatments compared to the no herbicide treatment. A negative linear correlation (R^2=0.1327) was observed between cover crop biomass produced and weed emergence. Weed emergence increased over time but preemergence herbicides were able to decrease emergence below levels

observed in the non-treated at ~42 DAP. This data suggests that cover crop biomass and preemergence herbicides can help to suppress early season weed emergence in soybeans.

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Abbreviations

ICL	Integrated Crop-Livestock
SOC	Soil Organic Carbon
AMF	Arbuscular Mycorrhizal Fungi
POXC	Permanganate Oxidizable Carbon
MBC	Microbial Biomass Carbon
WSA	Water Stable Aggregates
PR	Penetration Resistance
$AUC_{C.I.}$	Area Under the Curve for Cone Index
OM	Organic Matter
WREC	Wiregrass Research and Extension Center
EVSREC	E.V. Smith Research and Extension Center
TVREC	Tennessee Valley Research and Extension Center
DAP	Days After Planting

Chapter 1: Literature Review

Introduction

Soils in the southeastern United States have been degraded for hundreds of years. Historic agricultural practices such as conventional tillage and monocropping led to depletion of soil nutrients and soil erosion. This was a severe problem in the southeastern states because they relied heavily on production agriculture. Most arable land in the Southeast was in cultivation by the mid to late 1800's (Mitchell et al., 2007). In many of the southern states, cotton (*Gossypium hirsutum*) was the most widely planted crop. In the late 1800's, over 1.3 million ha of cotton was grown in Alabama and its production employed over half of the state's population (Mitchell et al., 2007). Cotton production mined extractable nutrients from the soil and added little organic matter (OM) back into the system. Additionally, the conventional tillage system used to grow cotton led to severe soil erosion. Extreme loss of topsoil has occurred across the Southeast, in some places totaling up to 24 cm of erosion (Causarano et al., 2006). The need for conservation practices to preserve the land, its productivity, and the environment is vital to survival of agriculture in the southeastern states. Conservation practices such as cover cropping, conservation tillage or no-tillage, and crop rotations have all been adopted at some level to protect the soil (Dorcas & Bergtold, 2020).

Conservation practices such as conservation tillage, cover crops, and crop rotations have been employed by farmers for decades to improve and protect the soil. Conservation tillage leaves 30% or more of the soil surface covered by residues, differing from the traditional inversion tillage practices. This reduces risks of erosion, allows for more water infiltration, and prevents decomposition of OM and release of carbon dioxide emissions from soil (Dorcas & Franklin, 2020). Crop rotations benefit cropping systems because they allow producers to break pest cycles and increase diversity within a cropping system. Rotating between a grass and legume, such as corn (*Zea mays*) and soybeans (*Glycine max*), allows for the system to fix some of its own nitrogen and possibly reduce the amount of nitrogen that needs to be applied. Crop rotations can add OM by incorporating high biomass crops, such as corn or wheat (*Triticum aestivum*), into a system with a crop that leaves little biomass, such as cotton. Crop rotations also increase diversity of soil organisms and enzymes by incorporating a wider array of OM into the system (Shah et al., 2021). A multitude of benefits to a cropping system can be obtained with cover crops such as reducing erosion, improving soil health, retaining soil moisture, and suppressing weed growth (Chu, 2017). Utilizing these practices together where applicable can increase the sustainability of agricultural production.

The world's population is continuously growing, and the amount of farmland is decreasing every year. At the same time, farms have become larger and more specialized. Specialization due to economies of scale and improved technologies have led to production of a large and cheap food supply (Hilimire, 2011). These specialized and intensified systems can have a detrimental effect on the environment through nutrient runoff, contaminated water sources, soil erosion, loss of biodiversity and increased greenhouse gas emissions (Lemaire et al., 2014). The specialization of agricultural lands has also led to a lack of diversity in production practices. The broad use of a few families of herbicides has led to herbicide resistance in numerous species of weeds. The development of transgenic crops and increased conservation practices led to widespread usage of herbicides, mainly glyphosate, in season. Increased usage of glyphosate led to selection for resistance within many weed species (Ian & Duke, 2017). Since the introduction of glyphosate resistant crops in 1996, the International Herbicide-Resistant weed database reports that 55 weed species have developed glyphosate resistance. This specialization of agriculture has brought forth new problems that need resolution.

Diversifying farms may be a more sustainable way to increase our food production while combating problems such as poor soil health and development of herbicide-resistant weed species. Integrated crop livestock systems and cover crops are both practices that were historically practiced on farmland around the world. These practices became less common with the intensification of agricultural practices and the usage of new technologies such as synthetic fertilizers (Hillimire, 2011; Klonsky & Ingels, 1998). Integrated crop livestock systems have potential to let parts of an agricultural system work in synchrony with each other to provide benefits that help producers be more profitable while protecting the environment and world's food supply.

Integrated crop livestock systems are not new practices, and documentation of mixing crops and livestock dates back 8 to 10 millennia (Russelle et al., 2007). Grazing corn fodder after harvest or grazing a cover crop allows livestock to obtain nutrients from biomass while returning some nutrients to the soil through manure. Integrated crop livestock systems can increase nutrient cycling, ecological diversification, and land use efficiency (Lemaire et al., 2014). Integrated crop livestock systems may also entice producers to use conservation practices, such as cover crops, because they can obtain economic gain from implementing them along with environmental and soil health benefits. Grazing cattle has potential drawbacks too. The footprint of a mature cow can exert the same amount of force as large field implements and causes compaction over time (Bezkorowanjnyj et al., 1993). Overgrazing cover crops may lead to increased compaction that is detrimental to soil structure and crop productivity (Carvalho et al., 2018). Overgrazing may also inhibit other benefits from cover crops such as nutrient retention and erosion control (Carvalho et al., 2018). Incorporating cover crops and cover crop grazing into a row crop system in the southeastern United States are two possible ways that producers may be able to improve their operations.

Conservation Tillage

Conventional tillage or inversion tillage was the standard land preparation in crop production for decades. Conventional tillage commonly involved moldboard plowing to invert the soil and a secondary implement to further break up clods and level the soil (Abdalla et al., 2013). Inversion tillage turns all residue on the soil surface under to provide a clean seedbed and is often used to improve seed to soil contact, reduce weed populations, and incorporate soil amendments; however, inversion tillage may negatively impact soil health by reducing water infiltration, decreasing soil moisture content, and increasing soil erosion, oxidizing OM, and destroying soil structure. (Radcliffe et al., 1988; Abdalla et al., 2013; Uri et al., 1999; La Scala et al., 2006). Continuous conventional tillage throughout the United States led to erosion and degradation of many soils. Intensive tillage also led to the Dust Bowl that devastated US agriculture in the 1930's. Negative effects of inversion tillage have led to increased adoption of conservation tillage in many production regions, including Alabama where 86% of cropland is managed under a form of conservation tillage (CTIC, 2017).

Conservation tillage does not disturb the entire profile and requires that at least 30% percent of residues be left on the soil surface. Several types of conservation tillage exist, including minimum tillage, strip tillage, subsoiling, and no-till (Morris et al., 2010). Minimum tillage involves running an implement across the soil that works at a shallow depth to loosen the soil surface and incorporate some residues. Strip tillage involves working a narrow strip where the seeds will be placed to disrupt hardpans and create a favorable seedbed without disrupting surface residue across the whole field. Non-inversion deep tillage, or subsoiling, works down to deeper depths. Subsoiling can reach depths greater than 30 cm and is designed to fracture hard pans that have formed in the soil to allow for plant roots to penetrate those layers. Soils can develop hardpans, or root limiting zones, and the large soil particle size and low OM content of many soils in the Southeast allow the soil to compact to greater strengths than roots can penetrate (Busscher & Sojka, 1987; Radcliffe et al., 1988). Busscher & Sojka (1987) demonstrated that conventional tillage created a zone of higher soil strength at a depth of 0.4 meters, which was the depth of tillage. In the same study, conservation tillage maintained an even soil strength throughout the soil profile but subsoiling under the row lowered soil strength in both plots. No-tillage does the least amount of surface disturbance, only breaking the surface to cut the seed furrow (Abdalla et al., 2013). Conservation tillage is designed to protect the soil from degradation and erosion, thereby maintaining a healthier soil.

In conservation tillage systems, residue from the previous crop along with the maintenance of soil aggregation protects the soil from erosion by lowering the aggregate dispersal effect of rainfall and increasing water infiltration (Zhang et al., 2007). The impact of rainfall on some Ultisols in the Southeast can lead to soil crusting from the impact of raindrops, which may limit infiltration rates (Radcliffe et al., 1988). Conservation tillage also protects soil organic carbon (SOC) from oxidation. Conventional tillage breaks up soil aggregates and exposes the SOC to the atmosphere where it is easily oxidized to carbon dioxide. Sequestering carbon has become a targeted practice by farmers as an effort to mitigate emissions of greenhouse gases into the atmosphere. Conservation tillage increases retention of soil aggregates and helps to preserve SOC (Tisdall & Oades, 1982). Remaining residue on the surface in conservation tillage systems can also increase habitat for many species of invertebrates and smaller mammals (Uri et al., 1999).

Conservation tillage systems may have both positive and negative effects on farm operations. Some studies have shown a yield reduction from conservation tillage systems (NeSmith et al., 1987), but most have shown no difference or a slight increase in crop yields under these systems, especially in the southeastern United States (Radcliffe et al., 1988; DeFelice et al., 2006). Conservation tillage may lower labor and fuel costs by reducing the number of trips across a field (Morris et al., 2010). Potential negative effects of conservation tillage such as increased compaction and a less suitable seed bed may be offset by other benefits it provides. Conservation tillage provides numerous benefits to the environment that make it a useful practice for producers to implement.

Crop Rotations

Crop rotations have numerous benefits to an agricultural system. Disease suppression, addition of OM sources to the soil, increase in available nutrients, and ability to change management practices are all benefits of crop rotation. Garcia et al. (2013) found that living soil cover in both the fall and spring can add more SOC to the system, increase soil microporosity, and improve overall soil health over time. Introducing a high biomass species, such as corn, into a cotton monoculture can increase SOC because of added crop residues. The Old Rotation at Auburn University is a good example as it shows that cotton rotated with corn under legume cover crops increased SOC over continuous cotton with no legume and cotton yield increased in the cotton/corn rotation plot with legumes and nitrogen fertilization over all of continuous cotton plots (Mitchell et al., 2008). Rotating between crops of different families decreases disease inoculum in the soil. For example, rotating between species such as peanuts (*Arachis hypogaea*) and corn can decrease disease persistence because corn is a non-host peanut diseases and its management may encourage growth of microorganisms that naturally control these diseases (Gil et al., 2008). A benefit of including legumes in a crop rotation is the addition of nitrogen to the soil (Mitchell et al., 2008). Legume residues release some fixed nitrogen as they degrade, making it available for the next crop, possibly reducing amounts of commercial fertilizer needed. Increases in SOC, reduced disease pressure, and introduction of legumes through crop rotation can work together to increase crop yields. Benefits are realized by producers across the nation and have led to the use of crop rotation on 82-94 percent of major crops grown in the United States (Wallander, 2013). Rotations containing cover crops are not as common but potential benefits of adding them to a rotation can further improve soil health and productivity.

Cover Crops

Cover crops have been used to achieve numerous goals related to improving cropping systems and the environment. There is evidence to show cover crops can improve soil health, prevent erosion, suppress weed growth, retain nutrients in the system, increase water retention, fix atmospheric nitrogen, and affect pest pressures (Baralbar et al., 2017; Causarano et al., 2006; Schipanski et al., 2014). Yield benefits have also been observed in some cases with continuous cover crops, by increasing in both yields and yield stability (Bergtold et al., 2017; Nouri et al., 2020; Lotter et al., 2009). However, slightly decreased cash crop yields have also been observed with use of cover crops under certain conditions (Qin et al., 2021). Cover crops and remaining biomass on the soil surface after their termination provide protection from erosion throughout the year and increase soil infiltration (Kasper & Singer, 2011). Effects on soil health from cover crops are positive to static, but many other factors (e.g., climate, soil texture) also affect soil health changes (Ruis et al., 2020). Cover crops can also be an important part of an integrated pest management (IPM) program by inhibiting weed emergence, deterring pests from a crop, inhibiting the reproductive stage of some insects, and attracting beneficial insects that feed on pests.

The benefits of cover crops have led to increased adoption of cover crops over the last few decades, with a 50% increase in hectarage to 6.23 million hectares from 2012 to 2017 (Wallander et al., 2021). This increase in adoption is due to perceived benefits of cover crops by producers and incentives provided by federal and state programs to promote cover crop implementation (Wallander et al., 2021). A survey conducted in South Carolina showed increased cover crop adoption, as many producers began to observe economic and environmental benefits that cover crops provide (Clay et al., 2020). While cover crop usage is increasing, the rate of adoption has not been as high as many had hoped. Widespread implementation of cover crops across all the major United States growing regions is hindered by costs of implementation including cost of seed, labor, fuel, and the lack of time to plant seed (Bergtold et al., 2017).

Benefits that a cover crop provides depend upon cover crop management, including species and cultivar selection. Seeding cover crops early and terminating late is important to obtain high biomass levels and to establish a good stand (Balkcom et al., 2023; Ruis et al., 2020). A study in Maryland found that mechanically and chemically terminated cover crops in late May compared to mid-April increased biomass by nearly 10-fold (Rosario-Lebron et al., 2019), but producing high biomass cover crops may cause other challenges for the cash crop such as cooler soil temperatures at planting (Qin et al., 2021). Drilling a cover crop can produce a better stand, and less seed can be used to obtain the same amount of biomass. However, it is more time consuming to drill than broadcast a high rate of seed (Haramoto, 2019). Cover crop management decisions need to be made based on the producer's goals. Cover crop species selection impacts the utility of a cover crop within a cropping system (Blanco-Canqui & Jasa, 2019). Three main families of plants are used for cover crops: Poaceae, Fabaceae, and Brassicaceae. Each family of cover crop species performs different functions (Snapp et al., 2005).

Small grains are the most planted cover crop due to their availability and growth habits (CTIC, 2023; Ruis et al., 2019). Many benefits from cover crops, such as OM additions and weed suppression require production of large amounts of biomass, especially in the temperate climate of the Southeastern United States. Grass cover crops help reduce loss of nutrients (e.g., nitrate) and scavenge nutrients deeper in the soil profile (Kasper & Smith, 2011). Grass crops are better at retaining nitrate than other species of cover crops. McCracken et al., (1994) found that a rye (*Secale cereale*) cover crop reduced nitrate leaching by 94% compared to a control. While small grain cover crops can improve nutrient retention, changes in nutrient management practices must be performed to maintain crop yields in subsequent crops. For example, residues may immobilize nitrogen, necessitating higher nitrogen fertilization of cash crops (Miguez & Bollero, 2006). On the other hand, high biomass and high C:N ratio of small grain cover crops helps their residues to persist for long periods of time to suppress weeds and prevent both wind and water erosion. Planting rye or sorghum (*Sorghum bicolor*) in late summer in Texas supplied adequate reductions of wind erosion compared to fallow (Bilbro, 1991). McDonald et al. (2020)

found that a wheat cover crop ensured a better cotton stand in the Texas panhandle because aboveground biomass prevented damage to cotton seedlings from wind erosion. A study in Western Kentucky found that cereal rye provided enough ground cover to reduce soil erosion below the tolerable soil loss for those soil types (Frye et al., 1985). Studies have shown that grass cover crops, such as rye and grain sorghum, can increase the percentage of water stable aggregates and other soil health indicators (Blanco-Canqui & Jasa, 2019). Small grains are non-host for some pathogenic nematodes such as southern root-knot nematodes (*Meloidogyne incognita*), so growing them does not allow for populations to reproduce during that season (McSorley, 2011). Strip tilling into cover crop residue also confuses pests such as thrips (*Thysanoptera* spp.), causing them to have trouble finding the host and lowering the amount of damage caused to a crop. Teows et al., (2010) found that planting cotton into a rolled rye cover crop significantly lowered thrip numbers per plant and kept insects below economic thresholds for 66% more of the sampling dates than the control. Conversely, some pest populations may be increased by cover crop as Duiker & Curran (2005) found increased slug populations in rolled rye cover crops in the Mid-Atlantic region during wet growing seasons.

Legumes such as crimson clover (*Trifolium incarnatum*) and hairy vetch (*Vicia villosa*) are best known for adding nitrogen to the system through nitrogen fixation. Legume cover crops can produce biomass levels as high as small grains but on average their levels are lower (Daniel et al., 1999; Ruis et al., 2019). Legumes have a lower C:N ratio than small grains, so they degrade faster, releasing some nitrogen in the biomass back into the system for uptake by other plants. Consistently incorporating legume cover crops into a rotation may help maintain high cash crop yields and lower supplemental nitrogen demands from the steady addition of organic nitrogen (Nouri et al., 2020). A five-year study in western Kentucky found that continuously using hairy vetch as a cover crop increased yield in plots with no added nitrogen by over 250% after five years compared to fallow (Frye et al., 1985). The same study found that both crimson clover and hairy vetch decreased soil erosion to acceptable levels for the soil types. A study by Miguez & Bollero (2006) found that a legume cover crop increased corn yields at all nitrogen rates when compared to no cover crop. Soil organic carbon data from the Old Rotation at Auburn University in the early 1990's shows that SOC in the winter legume plot (0.9% SOC) was double that of the no cover cover plot (0.4% SOC) at the 0-15 cm depth (Mitchell et al., 2008). Olsen et al., (2006) found that crimson clover cover crops significantly reduced thrips on both cotton and peanut plants and reduced early season damage from thrips.

Brassica species of winter cover crops such as purple top turnips and tillage radish can provide numerous benefits. Some studies have observed reduced compaction in hardpan layers from tillage radishes penetrating deeper into the soil (Chen & Weil, 2010). Brassica species may also produce high biomass values when sown early due to their ability to grow well in the fall (Baralbar et al., 2018). Chen & Weil, (2010) found that forage radishes had more roots penetrate past 10 cm in the soil profile under high compaction, but soil strength was not measured directly for these plots. William & Weil, (2004) found that a forage radish (*Raphanus* spp.) cover crop was able to penetrate through some compacted layers of the soil, allowing roots of the subsequent soybean crop to follow channels created by the radishes. An increase in soybean yield was also observed in these plots. Weed suppression can also be achieved with brassicas such as forage radish. Lawley et al., (2012) found that the fast growth of brassicas in the fall suppressed winter annual weeds but suppression of summer annuals was short lived into the growing season due to the rapid deterioration of the biomass. Brassica species such as white and black mustard can suppress nematodes by releasing biofumigants. Curto et al., (2016) found that black mustard and land cress significantly decreased the populations of southern root knot nematodes.

Combinations of cover crop species are also commonly used to obtain a mix of benefits provided by each species. Species diversity in a cover crop mix allows producers to pick and choose species that will perform functions that they want out of a cover crop (Ruis et al, 2020). Baralbar et al., (2017) found that a monoculture of cereal rye produced a similar amount of biomass as three- and four-species mixtures that contained brassicas and legumes. Mixtures that produce high biomass with lower small grain seeding rates can allow other goals (e.g., nitrogen fixation, pollinator habitat) to be obtained by incorporating higher rates of other species (Baralbar et al., 2017). An erosion study on an Ultisol in South Carolina found that a rye/vetch cover crop decreased soil loss by 62% (Langdale et al., 1991). A multisite study in Alabama found that cover crop monocultures of rye and clover and mixtures of rye-clover, rye-radish, and rye-clover-radish increased SOC and permanganate-oxidizable carbon (POXC) in the silt loam soils of the Tennessee Valley region but had little to no effects on SOC and POXC in loamy sand soils of South Alabama (Decker et al., 2022). The same study showed mixed effects of cover crops on soil strength and wet aggregate stability. While cover crop mixtures do introduce more plant diversity to a system, Florence and McGuire, (2020) found that mixtures on average do not perform better or worse than a high performing monoculture when evaluating soil moisture, weed suppression, cover crop and cash crop yields, soil biology, and nutrient retention. Mixtures still made improvements over fallow conditions, so using a mixture to alleviate compaction or increase the C:N ratio of aboveground biomass may be reasonable. A mixture of cover crops may also be more desirable for grazing because multiple species may provide a more nutritious food source for livestock and may extend the grazing period length. A mixture may be a valuable resource for some producers based on goals they want to meet with their cover crop.

Weed Management with Cover Crops

Conventional tillage and cultivation were the standard method of weed control in agriculture for most of history. The development of herbicides in the mid-20th century led to a combination of tillage and herbicide usage. The push for conservation tillage led to the use and reliance on herbicides to control weeds (Koskinen & McWhorter, 1986). Biological systems are forever evolving, and the switch to a reliance on herbicides versus tillage for weed control has led to an ecological shift in many of the common weed species foumd in cultivated crops today. Small-seeded grasses and annual weeds, such as common lambsquarter (*Chenopodium album*), horseweed (*Conyza canadensis*), Palmer amaranth (*Amaranthus palmeri*), foxtails (*Seteria* spp.), and quackgrass (*Elymus repens*), became dominate weed species under conservation tillage because weed seeds were now closer to the surface where they can emerge easier while larger seeded weeds such as velvetleaf (*Abutilon theophrasti*) and cocklebur (*Xanthium strumarium*) became less of a problem (Koskinen & McWhorter, 1986). Widespread use of broad-spectrum herbicides has led to development of herbicide resistant weeds, mainly to glyphosate (Heap & Duke, 2017; Norsworthy et al., 2008). The need for alternative methods of weed control to diversify management approaches to control or suppress these weeds and preserve the remaining chemistries vital to continuation of conservation tillage practices and high yields.

Weeds have adapted to their environments to help them compete with desired crops. They produce large numbers of seeds, grow quickly, both vegetatively and reproductively, and can stay viable in the soil for long periods of time. Sosnoskie et al., (2013) found that 10-15% of Palmer amaranth seeds were still viable 36 months after burial in the top 4 inches of the soil, while more seeds were still viable at deeper depths, but lay dormant. Many plants require a level of phytochrome red (Pr) and phytochrome far red (Pfr) light and a certain soil temperature to break dormancy and emerge (Batilla & Benech-Arnold, 2014). Using a combination of conservation tillage and cover crops may allow for higher seed fatality and prevent germination of seeds due to unfavorable conditions to break seed dormancy. Cover crops have different mechanisms for weed control. Some cover crop species, such as cereal rye and barley (*Hordeum vulgare*), produce allelopathic chemicals that can inhibit seed germination (Creamer et al., 1996). Allelopathic chemicals can be leached out of the remaining residue and released in the rhizosphere while the plant is growing. Substances such as benzoxazinones, can be released in the rhizosphere by oats. Radishes release some glucosinolates which can act as allelopathic chemicals to some species of weeds (Strum et al., 2018). Strum et al., (2018) found that both black oats (*Avena strigosa*) and oilseed radishes had the ability to suppress weed growth by over 25% through allelopathic chemicals. The key to weed suppression by cover crop monocultures and mixtures is high biomass production (Palhano et al., 2017). Lawley et al., (2011) found that forage radishes were able to supply strong early season weed suppression in a no-till corn system, but it did not persist long into the season due to degradation of the residues. A study by Pittman et al., (2020) in the Mid-Atlantic region of the U.S. found for 50% suppression of redroot pigweed at 4 and 6 weeks after termination, 2,800 and 5,280 kg ha^{-1} of biomass must be produced. Weed suppression of smaller seeded weeds can be achieved past 6 weeks but amounts of biomass to achieve at least 50% weed suppression should exceed 7,500 kg ha^{-1} (Pittman et al., 2020). The best weed suppression comes from grass species or mixtures with a grass species because they consistently produce higher biomass residue (Baralbar et al., 2017). A study in Georgia with multiple sites found that including a rye cover crop significantly decreased Palmer amaranth populations in most plots containing rye compared to the fallow (Hand et al., 2019). Mixtures can contain small amounts of a grass species and still provide sufficient weed suppression. Lawson et al., (2015) found that a 25-75% mixture of rye and hairy vetch provided the same amount of weed suppression as a 50-50% mixture of these species and gave the added benefit of more legume biomass. Planting an aggressive cover crop species early, such as cereal rye, may provide suppression of winter annuals in the fall and also suppress summer annuals in the spring when it starts to grow again (Baralbar et al., 2017).

Management practices for cover crops can affect weed suppression. Rolling the cover crop creates a mat over the soil surface that may improve weed suppression compared to leaving it standing, however, differences in weed suppression between standing versus rolled cover crop biomass have been hard to observe (Kelton et al., 2015; Ashford & Reeves, 2003). Planting date contributes to how much biomass is produced by the cover crop. Kelton et al., (2015) found that planting the cover crop earlier led to higher biomass production, which contributed to higher suppression of Palmer amaranth and smallflower morningglory (*Japonica tamnifolia*) at 21 days after planting (DAP) and of smallflower morningglory at 45 DAP. Terminating the cover crop closer to the time of planting can also increase biomass production which contributes to longer weed suppression (Rosario-Lebron et al., 2019). Drilling the cover crop can lead to a better stand which contributes to better ground cover and weed suppression (Haramoto, 2019). Cover crop species can also affect the length of weed suppression. Legumes have a lower C:N ratio so they decompose faster and do not supply long lasting ground cover. Wiggins et al., (2016) found that weed suppression by legume cover crops was no greater than that of no cover crop at 21 days after termination but cereal rye and wheat still maintained greater than 50% weed suppression. Cover crops may provide strong weed suppression in some cases, but it does not always provide adequate control (Wiggins et al., 2016). Whalen et al., (2019) found that rye and oat cover crops only reduced weed populations 38-40%. Cover crops can be a useful tool to incorporate into an integrated pest management plan for producers looking for alternative ways to control weeds.

Preemergence Herbicides

Cover crops have the potential to suppress weeds but will not completely control them. Preemergence herbicides can effectively control weeds early in the growing season when applied at planting. Preemergence herbicides can be incorporated into an IPM program to control weeds because it targets weeds at their most vulnerable stage and incorporates a different mode of action in the system to slow development of herbicide resistance (Sherwani et al., 2015). Preemergence herbicides must make soil contact to be effective in controlling weeds because they inhibit cellular growth of emerging seedlings (Ferreira et al., 2021). Preemergence herbicides also must be incorporated into the soil by rain or irrigation to be effective (Buhler, 1991). There are several modes of action of preemergence herbicides that target different plant pathways in weeds to control them (Sherwani et al., 2015). Chloroacetamide herbicides are a common mode of action used on many of the row crops in the United States that inhibit plant shoot growth. These herbicides work by inhibiting the synthesis of very-long chain fatty acids in the cell membrane and inhibiting the stem of the seedling from growing (Sherwani et al., 2015). Other preemergence herbicide groups affect shoots in different ways or inhibit root growth of seedlings. Some other herbicides such as the Photosystem II inhibitors can also be used as preemergence herbicides but do not kill the weed until it emerges. A full rate of preemergence herbicides applied with a burndown application can provide strong early season control. Albrecht et al., (2021) found that pairing preemergence herbicides such as flumioxazin with a nonselective herbicide can provide over 95% control of *Conyza* spp. in soybeans 35 days after application. Gazola et al., (2021) found similar results with multiple preemergence herbicides when examining their efficacy on grass and broadleaf species.

Pairing preemergence herbicides with cover crops can increase weed suppression up to levels of a system that relies on postemergence herbicide usage alone, while using less herbicides (Reeves et al., 2005). Preemergence herbicides applied at the proper rate can help to reach 90% weed suppression in a conservation tillage, cover crop system (Reeves et al., 2005). Hand et al., (2019) found a cereal rye cover crop paired with a broadcast preemergence and postemergence herbicide plan achieved the best Palmer amaranth control compared to banded herbicides or no cover crop in cotton production. Cover crops are effective at improving weed control during the growing season but to achieve successful management of weeds they should be paired with a herbicide program (Hand et al., 2019; Wiggins et al., 2016). It is possible that high biomass cover crops can intercept and prevent preemergence herbicides from making it to the soil. (Whalen et al., 2019). Whalen et al., (2019) found that waiting to terminate the cover crop seven days prior to planting allowed for more biomass to accumulate and caused a 30% decrease in weed suppression with the preplant residual program compared to terminating 21 days prior to planting. This was attributed to less preemergence herbicide contacting the soil, and soil tests from each of the plots found that herbicide residues in the soil were lower in plots treated 7 days prior to planting compared to plots treated 21 days prior to planting (Whalen et al., 2019). More studies to examine the combined effects of preemergence herbicides with cover crops under different management practices are needed to find the most effective plan to provide early season weed suppression in row crops.

Integrated Crop-Livestock Systems

Integrated crop-livestock (ICL) systems have existed since the dawn of agriculture as humans raised livestock to consume, use as draft power, and to make use of raw materials that could not be directly consumed by humans. Integrated crop-livestock systems use resources produced from one commodity to help produce the next commodity. There are numerous types of ICL systems from spatially separating crops and livestock and using products from one system to produce another to combining them on the same land at different periods of time (Hilimire, 2011). Efficient ICL systems allow producers to intensively manage their land to increase productivity, make use of otherwise unused resources, possibly cut back on input costs, decrease soil erosion, and improve soil health (Russelle et al., 2007; Hilimire, 2011; Maughan et al., 2009; Franzluebbers, 2007; Kumar et al., 2019). The need to increase agriculture productivity due to population growth and loss of farmland has led to a renewed interest in ICL systems to sustainably intensify production systems (MacDonald & McBride, 2009).

Implementing ICL systems in the southeastern United States can be dependent on goals of the producer. Sod-based rotations and seasonal cover crop grazing are two methods to rotate crops and livestock on the same land (Kumar et al., 2019). In the southeastern United States, forage supply is often limited in the winter months because warm season grasses are dormant. Grazing cattle on winter cover crops supplies additional forage during a season where forage is typically short, upcycles nutrients from the crop biomass, and helps growers to recoup some revenue from the cover crop (Franzluebbers, 2007). Cover crops have been used extensively in this region to provide various soil and environmental benefits. Some reserves producers may have about an ICL system are about its effects on crop yield, soil moisture, and soil physical properties. Livestock traffic may increase soil compaction and removal of biomass may reduce the ability of the soil to retain moisture and make it more susceptible to erosion Franzluebbers & Stuedemann, (2008). Some studies from the US corn belt have found that ICL systems that grazed cover crops also had a cash crop yield increase (Maughan et al., 2009). In the southeastern United States, (Franzluebbers & Stuedemann, 2007) found that grazing cover crops increased soil penetration resistance (PR) and had a negative effect on yield under no-till management but no effect under conventional management. In the coastal plain of Alabama, a cotton yield increase was observed under an ICL system that employed deep, non-inversion tillage and conservation tillage practices (Siri-Prieto et a.l, 2007). High stocking rates and biomass removal with grazing of livestock can lead to negative effects on cash crop yield. Maintaining a proper stocking rate, leaving some biomass on the soil surface, and non-inversion deep tillage are all methods to reduce negative effects of grazing (Franzleubbers, 2007, Siri-Prieto et al., 2007).

This intensive system can be costly to implement if you do not already have the needed infrastructure in place (Kumar et al., 2019). It can be costly to manage as well because of added time commitments and input costs. Studies across the US have seen an economic return of 80-

311 dollars per hectare in added net revenues to the system from grazing cover crops in the southeastern United States (Siri-Prieto et al., 2007; Franzleubbers, 2007; Schomberg et al., 2014). Increased net revenues and minor effects to crop yields could make these ICL systems a viable production practice for some producers. More research to confirm the benefits and consequences of ICL systems in the Southeast will be important to help producers implement these practices.

Soil Health Indicators

Soil health has become an increasingly popular topic in the agriculture industry. The term soil health refers to the soil's ability to function as a living system that can support life of humans, plants, animals, and microorganisms (Stott, 2019). Determining soil health is a holistic approach that examines numerous soil health indicators that represent chemical, physical, and biological properties of the soil and observe how they change over time. Many of these soil characteristics are related to management of the soil. The conventional method of agricultural production relies upon extensive tillage practices that can degrade the soil's health. The USDA NRCS has established four main principles to drive soil health. They are to maximize presence of living roots in the soil, minimize soil disturbance, maximize soil cover, and maximize system biodiversity. Conservation practices, such as conservation tillage, cover crops, and crop rotations; that limit losses to the soil can help to improve the environment and productivity of agricultural land. The ability and extent of change to soil health is dependent on soil type and climate. The southeastern United States has a warmer climate and sandy textured soils so the accumulation of OM and improvement of other soil health properties may be lower and slower than in other soils. Observing changes in soil health takes time, so long-term studies focused on specific soil health indicators need to be conducted to determine the full scope of benefits from these practices.

Soil health indicators are soil properties that can be used to evaluate how the soil functions as a system. All SOC including non-decomposed plant matter, active carbon sources such as amino acids, and stable organic carbon such as humus are forms of OM (Arias et al., 2005). Organic matter is a driver of soil functions because it can affect water holding capacity, cation exchange capacity, and provides substrates for microbial activity (Bronick & Lal, 2005; Diacono & Montemurro, 2011). Roughly 58% of OM is composed of soil organic carbon (SOC). Sequestering carbon in the soil is thought to be an effective way to mitigate climate change by reducing the supply of carbon dioxide released into the atmosphere (Lal, 2004). Soil health indicators, including OM, are used to measure changes in soil processes and characteristics due to management changes (Doran & Zeiss, 2000).

Soil health indicators are separated into three separate categories: chemical, physical, and biological. Chemical soil health indicators focus on presence and retention of elements in the soil. The retention of elements such as carbon and nitrogen in soil are topics of discussion in many circles because of their harmful effects as pollutants. Some chemical soil health indicators are SOC, active carbon, soil pH, and available nutrients (Stott, 2019). Chemical soil health indicators are drivers of plant growth because they relate to many nutrient cycles, microbial processes, and available nutrients.

Physical soil health indicators can include water stable aggregates (WSA), PR, and bulk density. Physical soil health indicators affect understand the movement of solution in the soils as well as protection of OM. Soil aggregates can form through bonding of soil particles to OM that protect it from degradation (Jastrow et al., 2007). Increased soil strength and bulk density correlate to reduced pore space which leads to decreased water flow and increased root limitations (Horn et al., 1995). Maintaining good soil structure is important to maintaining soil productivity.

Biological soil health indicators such as soil microbial biomass carbon (MBC) and enzyme activities react quicker to management changes than chemical and physical indicators because they are related to dynamic, living populations (Acosta- Martinez et al., 2004). Microbial diversity and population sizes can give insight into how inhabitable the soil is, length of nutrient cycles, and amount of OM in the soil (Arias et al., 2005). Microbial biomass is also a sink for SOC. Different management practices such as amount of tillage and crop rotations have the potential to affect biological activities in the soil (Mann et al., 2019). Using chemical, physical, and biological soil health indicators provides a way to quantify how production practices affect dynamic cycles that dominate soil's ability to act as a functioning environment.

Soil Organic Carbon

Soil organic carbon is a collection of all organic carbon in the soil and serves as a soil health indicator because it is a large component of OM. Carbon is an important element to all living organisms because it is the building block of all organic life forms. When carbon-based life forms deteriorate, carbon can be stored in the soil or lost to the atmosphere or water as carbon dioxide. Soil is a large sink for carbon and has a natural flux of inputs and outputs that human activities can interrupt (Schlesinger & Andrews, 2000). Sequestering carbon in the soil by converting it into more stable forms may reduce carbon fluxes to the atmosphere (Prescott, 2010). Soil organic carbon quality and quantity is dynamic. Variables such as climate, soil type, soil mineralogy, topography, vegetation, and various other biotic and abiotic factors may affect the concentration of SOC in the soil (Lal, 2016; Feng et al., 2013). Soil organic carbon is often low in soils of the southeastern United States because of the humid, high temperature, and high rainfall climate that accelerates OM decomposition (Franzluebbers, 2005). Sandy textured soils protect little SOC because less soil aggregates form compared to finer textured soils (Bronick & Lal, 2005). Changes in SOC depends on the initial level of SOC as soils high in SOC do not see a large increase in SOC when management practices are changed (Abdalla et al., 2013).

Agricultural practices that reduce SOC oxidation and increase additions of SOC to the soil help to improve soil health. Reducing tillage, maintaining living cover for a longer portion of the year, and addition of various types of OM can increase the amount of carbon sequestered in a system (Franzsluebbers, 2005). Tillage can affect carbon dynamics in the soil. Conservation tillage causes less soil disturbance, slowing the oxidation of SOC. Franzluebbers, (2010) reviewed studies across eight states in the southeastern United States and found that conservation tillage led to an increased carbon sequestration rate of 0.45 Mg C ha yr^{-1}. This review suggests that over 63% of the time at least 0.25 Mg C ha yr^{-1} will be sequestered under no till (Franzluebbers, 2010). Wood et al., (1992) found that SOC was significantly higher under no-till compared to conventional tillage after ten years of management. Tillage also affects stratification of SOC in the soil. Conventional tillage turns under residue and distributes SOC throughout the soil profile. Conservation tillage practices leave most or all residue near the surface so higher levels of SOC will be detected in the upper 0-5 cm of the soil (Causarno et al., 2008). A 15-year tillage study in Nebraska found that no-till treatments increased SOC by 4.6-11.6 Mg ha^{-1} compared to treatments that disturbed the soil (Varvel & Wilhelm, 2010).

Quality and quantity of OM can also lead to differences in SOC. Crop rotations and cover crops can both introduce high biomass producing crops (rye, crimson clover, corn) into a system with crops that produce little biomass such as cotton. The C:N ratio, amount of biomass, and incorporation method of biomass all affect how these additions affect SOC (Sainju et al., 2002; Franzluebbers, 2010). Biomass with high C:N ratios often sequester more carbon because they do not break down as fast. A cover crop study on sandy loam soils with conventional tillage in Georgia found that all cover crop treatments had higher SOC than the control, but only cereal rye led to an overall increase in SOC from the start of the experiment (Sainju et al., 2002). A study in North Alabama found that corn with a wheat cover crop sequestered 21% more SOC than soybeans did with the same cover after ten years (Wood et al., 1992).

Some studies suggest that ICL systems in the Southeast can be managed with conservation tillage and not observe negative impacts to production. A 38% increase in SOC was observed in a three-year study in south Alabama in subsoiled plots compared to conventional tillage in an ICL system rotating cotton and peanuts with cover crops in the winter (Siri-Prieto et al., 2007). Fultz et al., (2013) found a 22% increase in SOC in an ICL system over 13 years compared to continuous cotton in the semiarid West Texas climate. Less soil disturbance and more permanent ground cover promotes transformation of SOC into more recalcitrant forms (Fultz et el., 2013). Being able to manage these systems with minimum tillage and high biomass crops could allow for greater SOC sequestration because of added OM from the system. More studies examining ICL systems on sandy soils could confirm their impact on SOC.

Permanganate Oxidizable Carbon

Permanganate oxidizable carbon (POXC) is the active, or labile, fraction of SOC. Permanganate oxidizable carbon may be more sensitive to change because it can turnover in a short amount of time from weeks to a couple months, while other more stable forms of SOC can take decades or centuries (Tiroi-Padre & Ladha, 2004). With a faster turnover than SOC, POXC is potentially more sensitive to management changes (Plaza-Bonilla et al., 2014). Culman et al., (2012) found that POXC values were positively correlated with particulate organic matter and microbial biomass carbon (MBC) which are other methods of measuring carbon in the soil that can react to management changes.

Permanganate oxidizable carbon is affected by tillage. Singh et al., (2020) observed a significant larger amount of POXC in no-till production compared to conventional tillage practices such as moldboard plowing and chisel plowing in the top 15 cm of soil after a thirty-nine-year, continuous soybean rotation. Tillage can also change stratification of POXC in the soil. Incorporation of residue and oxidation of carbon sources are the leading causes of these changes. No-tillage management concentrates organic inputs near the surface of the soil, building more POXC in the surface layers of the soil but less at deeper depths. An 11-year tillage study on an Entisol in Northeast Spain comparing no-tillage to conventional tillage found a 60% increase in POXC in the top 5 cm of soil but a decrease at all other soil depths (Plaza-Bonilla et al., 2014). Xue et al., (2018) found that subsoiled treatments with residue incorporation had the highest POXC readings in the 20-50 cm range.

Cover crops can affect POXC concentrations in the soil. Organic additions are shown to have a greater effect on POXC concentrations than tillage. Permanganate oxidizable carbon under no-till with winter wheat and double cropped soybeans and soybeans with a winter wheat cover crop was 465 and 417 mg kg^{-1} of soil compared to no-till soybeans alone with 301 mg kg^{-1} of POXC in soil (Singh et al., 2020). Crop rotations also affect POXC values in the soil. A study showed an overall POXC increase in a rotation of corn-soybean-wheat with cover crops compared to continuous corn (Culman et al., 2013). This is primarily due to the increase in diverse quality of organic inputs to the system. Additions of OM of different qualities and quantities has the largest influence on POXC. Ghimire et al., (2019) found that POXC levels were higher under an oat, pea/oat, and a six species cover crop mix compared to a fallow control. These three treatments produced the highest biomass in that study, also adding the highest amount of carbon to the system. The addition of more carbon to the system contributed to the higher POXC in these plots (Ghimire et al., 2019).

The effects of an ICL system on POXC has not been studied extensively and more research is needed. An ICL study in Georgia found that grazing cover crops had no consistent positive or negative effect on SOC fractions (Franzluebbers & Stuedemann, 2008). More research needs to be conducted to understand the effects of ICL systems on POXC. If an ICL system does not cause significant negative impacts on POXC and other carbon pools in the soil, the system can be used by producers trying to increase diversity within their operations.

Water Stable Aggregates

Water stable aggregates (WSA) are a suggested physical soil health indicator. Measuring WSA quantifies the soil's ability to resist erosive forces (Kemper & Rosenau, 1986). Water stable aggregates are groups of cohered soil particles that can resist the erosive forces of runoff, rainfall, slacking, and the swelling of clays (Kemper & Rosenau, 1986). Protection of SOC from oxidation, improving soil porosity and drainage, and improving water holding capacity are all possible benefits of improved WSA (Tisdall & Oades, 1982). Soil aggregates can be formed by organic associations with partially decomposed OM, secretions from plant roots, and secretions from soil microorganisms (Tisdall & Oades, 1982; Morel et al., 1991). Soil organisms, such as arbuscular mycorrhizal fungi (AMF), have helped increase WSA in soils because they secrete glomalin which can serve as a binder of soil particles (Wilkes et al., 2021). Positive relationships between groups of Gram-negative bacteria and WSA were observed in numerous sampling sites across Eastern Canada (Mann et al., 2019). Morel et al., (1991) found that additions of mucilage from corn roots increased soil aggregation compared to the control and other organic amendments in silt loam and silty clay soils. Different sources of OM influence changes in WSA because they degrade at different rates in soil over time (Abiven et al., 2007). These soil aggregates can bind together and stabilize SOC because they prevent decomposition and oxidization by protecting it within aggregates (Jastrow et al., 2007). Relations between other soil health indicators and WSA are important to consider when looking at soil health.

Tillage can affect WSA. Tillage events break naturally formed bonds holding together macro- and microaggregates through physical disruption, leading to oxidation of the OM bonding them together. Minimal tillage or no tillage events will disturb the soil profile less which should prevent these processes from happening. Wilkes et al., (2021) found that fields under zero tillage management had a higher percentage of WSA than conventionally managed fields on all sampling dates. No tillage practices increased macroaggregates significantly in surface layers compared to more intense tillage strategies in Ultisols of the southeastern United States (Beare et al., 1994). Singh et al., (2020) showed a 50% increase in WSA in no-till plots compared to conventionally tilled plots in a thirty-nine year tillage management experiment on an Alfisol in West Tennessee. These increases in WSA from conservation tillage practices are related to increased levels of SOC and redistribution of the SOC in the soil profile.

Crop rotations and diversified cropping systems can also affect WSA. Practices that introduce different sources of OM into the system such as a rotation between different crops or use of cover crops. Haynes & Swift, (1990) found that switching cropland over to pastureland can increase WSA. Soil usage and duration also affects WSA levels. A steady decrease of WSA on loamy soils was observed when grasslands were converted to cropland and worked for three years (Angers et al., 1992). McVay et al., (1989) found that cover crops increase WSA compared to fallow plots in a Coastal Plain soil. Legume cover crops significantly increased WSA over small grain cover and fallow plots (McVay et al, 1989). Winter cover crops increased WSA in all plots compared to the control on a silt loam soil in Illinois (Villamil et al., 2006).

Water stable aggregates may also be affected by ICL systems. Integrating livestock into a system introduces carbon in another form, manure, which may increase soil carbon in aggregates more quickly. Compaction may be increased by livestock traffic which may leave less pore space for carbon sources to be transported through the soil that help soil particles bind together. A three-year study in Nebraska grazing a rye cover crop found that there was no difference between WSA amounts in grazed and non-grazed plots (Blanco-Canqui et al., 2020). Franzluebbers & Stuedemann, (2008) found that WSA was not affected by grazing on an Ultisol in Georgia two and a half years after the initiation of the project. More studies need to be conducted to examine how an ICL system can affect WSA.

Penetration Resistance

Soil penetration resistance (PR) is a measure of the soil's structural strength. Penetration resistance reflects how much force it takes to push a rod through the soil and can be affected by bulk density, soil-metal friction, and moisture content (Benough & Mullins, 1990; Vaz et al., 2011). Soil moisture has a major effect on PR readings because lower soil moisture can lead to artificially higher results due to increased friction between the soil and probe surfaces (Vaz et al., 2011). Soil penetration positively correlates with compaction, which can cause problems for plant root growth if PR is above 2,000 kPa (Williams & Weil, 2004; Laboski et al., 1998). Compaction is a common problem in agricultural settings that can be caused by equipment traffic, hardpans formed by continuous tillage, and livestock movement (Batey, 2009; Raper & Kirby, 2006). Compaction can lead to lower crop yields, increased runoff and erosion, less pore space, anaerobic zones in some soils, and restricted rooting zones (Batey, 2011),

Tillage methods influence PR. Conventional tillage can loosen the soil and lower PR. Continuous tillage may have detrimental effects on PR by forming a hardpan at the shear layer of a tillage implement (Chen & Tessier, 1997). Disturbance of surface layers allows reconsolidation of soil particles that may form root limiting barriers and tillage applies force to the layer below its working depth which causes a hardpan to form (Raper et al, 2005). No-till and reduced tillage systems can also develop hardpans that form deeper and are less compact. A study performed in Georgia on a sandy clay loam soil found PR to be significantly higher under no-till compared to conventionally tilled soils (Franzsluebber & Stuedemann, 2008). While PR may be increased by no-till, negative effects on yield may not always be observed. Nunes et al., (2018) found that no-till management significantly increased PR over conventionally tilled loamy sand soils by 0.5 MPa in the first 15 cm of soil but corn yield was unaffected and no differences in corn yield and PR were observed in a silt loam soil. Some tillage practices, such as subsoiling, can be used to alleviate PR. Raper et al., (1998) found that conservation tillage that included subsoiling under the row increased depth to the hardpan and decreased soil strength in trafficked and non-trafficked row middles compared to conventional tillage in a sandy loam soil in Alabama.

Cover crops can influence PR. Cover crops can help prevent or alleviate PR because some species such as tillage radishes and rye have strong root systems that could potentially penetrate compacted, root-limiting soil layers (Marshall et al., 2016). Three trials on sandy soils in South Carolina found that cover crops significantly reduced PR in no-till plots and increased cotton yield 38% (Marshall et al., 2016). Forage radish and rye cover crops were found to penetrate compacted soils layers and increase soybean rooting depth in a study in Maryland (Williams & Weil, 2004). Tap-rooted cover crops such as forage radish and Diakon radish were able to penetrate compacted layers of soil with PR readings of more than 2,000 kPa in sandy loam and silt loam soils of the Mid-Atlantic (Chen & Weil, 2010).

Integrated crop-livestock systems may also affect PR. Livestock traffic on the field can cause increased PR in surface soil layers. High stocking rates could cause greater PR increases due to more traffic and removal of more forage (Pires da Silva et al., 2003). Pires da Silva et al., (2003) found that stocking rates of more than 4.5 animal units ha^{-1} significantly increased PR past 3 MPa, which is considered root limiting to many plants. A cover crop grazing study in Georgia found that PR was higher under grazed than non-grazed plots in the top 10 cm of soil under conventional tillage (Franzluebbers & Stuedemann, 2008). George et al., (2013) found that the bulk density of soil changed little between grazed and non-grazed plots of a rotation containing a two-year sod-based component. An increase in bulk density correlates to more PR because soil particles are packed closer together. With limited research on the effects of cover crop grazing on PR in the Southeast, more research would be beneficial to understand their relationship.

Microbial Biomass Carbon

Microbial biomass carbon (MBC) measures the fraction of soil carbon within living soil organisms. Soil microbes function as the primary degradation pathway of OM which makes them a driver in soil nutrient cycling (Dalal, 1998). Roughly 5% of the SOC stored in the soil is MBC (Dalal, 1998). Turnover of MBC can be completed in as few as six months compared to other SOC stocks which can sometimes take decades to see changes; therefore, MBC can be used as a good early indicator of changes in soil health due to its sensitivity to management changes (Yuan et al., 2018). Microbial biomass carbon can be affected by a variety of factors including tillage systems, crop rotations, residue retention, climate, soil texture, and pH (Singh & Gupta, 2018; Rice et al., 1996; Yuan et al., 2018; Curtin et al., 2012). Soil microbial populations are important to agricultural systems because they drive many soil processes. More diverse populations and higher populations of soil microbes can lead to higher nutrient turnover in the soil (Tate, 2017).

Different tillage systems can have an effect on MBC. Less tillage in a system leads to higher microbial activity in many cases. On the Coastal Plain and Piedmont soils of Maryland, conservation tillage showed an increase in MBC over conventional tillage on over 90% of the test sites with an average increase of 45% (Islam & Weil, 2000). In a 15-year study in a fine sandy loam soil in the Appalachians of North Carolina, Wang et al., (2011) found that MBC decreased in concentration from continuous grass to no-tillage to conventional tillage management. Different tillage practices can also change stratification of MBC in soils. Microbial biomass carbon decreased with depth across four sampling sites in a six-year, continuous corn trial of different tillage practices (Salinas-García et al., 2002). Microbial biomass carbon was 25-50% higher in the 0-5 cm depth for no-tillage and reduced tillage systems compared to conventional tillage, but it decreased with depth to match MBC levels of conventional tillage (Salinas-García et al., 2002).

Use of cover crops has been shown to affect MBC. Mendes et al., (1999) observed an increase in MBC from red clover and triticale cover crops in a vegetable production system in the Pacific Northwest after one year. An experiment in the Texas High Plains demonstrated that winter cover crops can increase MBC by 50% compared to a cropping system with no winter cover in semi-arid environments (Acosta-Martinez et al., 2011). It was also shown in this same trial that crop rotation can also affect MBC. A field of continuous cotton compared to a rotation of sorghum and cotton exhibited a 38% increase of MBC under the rotation after 5 years (Acosta-Martinez et al., 2011). Crop rotations introduce a variety of OM into a system and allows for some high and low biomass crops to be grown on the same site. Different residues can increase MBC and potentially increase microbial diversity. A twelve-year study comparing 5 different crop rotations showed an increase in MBC in all rotations over continuous corn (McDaniel & Grandy, 2016).

Integrated crop-livestock systems can influence MBC. Introducing livestock into a system changes forms of OM that are introduced into the system. Livestock manure contains more labile nutrients (Entz & Martens, 2011), which could provide a larger food source for microbes to feed on. A two-year study in Brazil testing different grazing intensities of a *Brachiaria ruziziensis* cover crop between soybean crops showed an increase in MBC across all grazing intensities over the non-grazed control at the end of the pasture cycle of the experiment (Silva et al., 2015). The same study only showed an increase in the least grazed plot over the non-grazed control after soybeans were harvested (Silva et al, 2015). George et al., (2013) showed that MBC increased significantly between grazed and non-grazed plots for non-irrigated plots, but no significant difference was observed for irrigated plots in a bahiagrass, cotton, peanut rotation in North Florida. More research should be performed to determine the effects of an ICL system on MBC.

Arbuscular Mycorrhizal Fungi Colonization

Arbuscular mycorrhizal fungi (AMF) are important soil fungi that fill a vital role in botanical systems around the world. Roughly 80% of higher plant species on Earth can form relationships with AMF (Bhantana et al., 2021). Arbuscular mycorrhizal fungi is an endomycorrhizal fungi that forms arbuscules and vesicles within plant roots and forms a network of extraradical mycelium in the soil (Malcová et al., 2001). A symbiotic relationship is formed where plants provide sugars and carbohydrates to the AMF for energy and the AMF provides additional nutrients and water to the plant (Piotrowski & Rillig, 2008). This relationship allows plants to obtain nutrients that are out of reach of their own roots. Arbuscular mycorrhizal fungi can help regulate plant stress by helping maintain water within the plant during drought and help to combat pathogens (Bhantana et al., 2021). AMF absorbs cations, such as phosphorus, from the soil solution and transports it into the plant, increasing plant nutrition (Kabir, 2005). Increased plant growth and higher plant phosphorus levels have been observed with higher AMF root colonization (Treseder, 2013). Tillage, crop rotations, soil pH, available nutrients, and organic additions can all affect AMF colonization and growth (Piotrowski & Rillig, 2008).

Soil disturbances such as tillage affect AMF populations. Conventional tillage inverts the soil and breaks up the AMF network. A study comparing abandoned land to conventionally tilled land found that higher amounts of AMF inoculum occurred in fields that have been undisturbed for 1-3 years (Barni & Siniscalco, 1999). Jansa et al., (2002) found that no-till treatments had a higher spore count compared to a conventional tilled treatment in a field in Switzerland. No-till or reduced tillage leaves more hyphae in place and may increase colonization in the future crop as its hyphae expands (Kabir, 2005). Evans & Miller, (1988) found that conventional tillage caused a significant decrease in inoculation intensity of AMF on maize and wheat.

Plant species affect AMF colonies as well. Barni & Siniscalco, (1999) found that the highest potential for AMF colonization was after perennials had established themselves on abandoned land and declined after trees became the dominant species. Growing different plant species may introduce better hosts for some species of AMF and increase the AMF inoculum and colonization in the soil. A study performed in western Kentucky comparing AMF populations in continuous soybeans, soybean/corn rotation, milo/corn rotation, and fescue/soybean rotation found that a significantly higher number of AMF propagules and higher AMF species diversity was observed across all rotations during the growing season (Hendrix et al., 1995). Cover crops keep living roots in fields for a longer portion of the year, allowing AMF to colonize and reproduce more. Lehman et al., (2012) found that fall cover crops doubled the number of AMF propagules found in the soil compared to fall fallow plots. A study from the semi-arid climate of New Mexico found that an oat cover crop increased AMF presence by 84% compared to a fallow treatment (Thapa et al., 2021). Cover crop mixtures may provide multiple hosts for AMF and increase its presence as Thapa et al., (2021) found that AMF presence was 20.5% higher in a cover crop mixture compared to a monoculture.

Little work has been conducted to determine the effects of cover crop grazing on abundance of AMF in the sandy soils and humid climate of the southeastern United States. Sekaran et al., (2021) found that ICL systems with cover crop mixtures in South Dakota increased levels of AMF compared to control plots with no cover. Integrated crop-livestock systems in these studies were not significantly different than non-grazed cover crops (Sekaran et al., 2021). Many forage grass species are colonized by AMF, allowing plants in these ICL systems to obtain extra moisture and nutrients through AMF. A study in the High Plains of Texas found that soils in both annual cover crops and perennial pastures had higher levels of AMF markers compared to soils under continuous cotton with no cover crops (Davinic et al., 2013).

Objectives

Diversifying agricultural operations to feed the growing world population through a more efficient and sustainable production system is an important question for today’s researchers. Producing more commodities and increasing profits per hectare will be important to help producers achieve the continually growing demand for affordable food. Cover crops have potential to provide many benefits that may improve the functionality and efficiency of some agricultural systems. Goals the producer wants to achieve with a cover crop determines the species selection and management techniques they use. Integrated crop-livestock systems show potential to be one way that producers in the southeastern United States could improve their production on the sandy Coastal Plain soils. Research to determine the optimum grazing period lengths to promote livestock production and crop productivity without harming soil health is needed. Research to study how conservation practices negate negative effects to soil health from an ICL system is also needed. Conservation agriculture practices such as reduced tillage and cover crops are proven to affect physical, biological, and chemical soil health indicators, but less work has focused on these practices in an ICL system.

Widespread, continuous use of herbicides has led to the development of herbicide resistant weeds that pose a major threat to productivity of cropping systems across the United States. The long, humid, and warm growing season of the southeastern United States poses a large challenge to control these weeds because numerous generations can emerge within a season before a crop can shade them out. Combining ground cover of high biomass cover crops with a preemergence herbicide may prevent germination of weeds later into the season. Studies to determine weed suppression abilities of these practices should be conducted to provide producers with reasonable expectations for these production practices.

Two objectives have been determined for the ICL system experiment, 1) determine the effects an ICL system has on yield and soil health in a peanut-cotton rotation with cover crops and 2) determine the optimum cattle grazing period to maximize livestock production, soil health, and crop productivity.

The objective of the weed suppression study are to 1) determine the effect of different combinations of cover crop seeding rates and nitrogen fertilizer rates on cover crop biomass production and 2) evaluate the combination of cover crop biomass and different preemergence herbicide treatments on weed suppression in soybean production systems in the southeastern United States.

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Chapter 2: Evaluating the Impacts of Different Cover Crop Grazing Intensities on Soil Health and Crop Productivity

Introduction

Soils of the southeastern United States have been degraded over the past few centuries by intensive agricultural practices such as monocropping, intensive tillage, and lack of organic additions to the soil (Mitchell et al., 2007). Extensive tillage across the farmland in the Southeast led to severe soil erosion, totaling 24 cm in some cases (Causarano et al., 2006). Farming practices, along with the warm, humid climate and sandy textured soils of the region, encourage turnover of organic carbon and have depleted stocks of soil organic matter (OM) (Franzluebbers, 2005). Organic matter provides many benefits to the soil, including increased water and nutrient holding capacity, improved soil aggregation, and increased microbial activity, making it the main driver of soil health (Bronick & Lal, 2005; Diacono & Montemurro, 2011). The need to protect and restore the health of these soils is important for preservation of agricultural production. Conservation practices such as conservation tillage, crop rotations, and cover cropping can help protect and improve these soils by adding OM and nutrients to the system, preserving soil moisture, reducing erosion, increasing biodiversity, and maintaining soil cover throughout the year.

Benefits of conservation tillage, crop rotations, and cover cropping are well documented (Radcliffe et al., 1988; Abdalla et al., 2013; La Scala et al., 2006; Garcia et al., 2013; Mitchell et al., 2008; Baralbar et al., 2017; Causarano et al., 2006; Schipanski et al., 2014). Conservation tillage has been widely adopted by producers because studies have exhibited its benefits to soil health and land stewardship, but also because producers can reduce labor and fuel costs without sacrificing yield (Oqieriakhi & Woodward, 2022). Diversified crop rotations can help reduce pest pressure, increase OM additions and biodiversity, and improve yield stability (Sindelar et al., 2016; Causarano et al., 2006), leading to greater adoption rates across the United States (Wallander, 2013). Cover crop adoption rates are not as high as other conservation practices (Wallander et al., 2021), and low adoption may stem from lack of time to plant cover crops during the harvest season or from perceptions that cover crops are not profitable (Clay et al., 2020). Benefits from cover crops often show that it takes several years to observe improvements, so it should be viewed as a long-term investment in the land (Bergtold et al., 2017). It is necessary to explore ways to obtain economic returns in the short term to encourage producers to implement cover crops. Grazing cover crops is one method that may allow producers to use a cover crop each year for economic gains, but impacts of grazing in a row cropping system on soil health and yields have not been widely studied in the Southeast.

Soil health is defined by the USDA-NRCS as "the capacity of the soil to function as a vital living ecosystem that supports plants, animals, and humans" (Stott, 2019). Soil health is often evaluated by examining physical, chemical, and biological soil properties that are sensitive to management changes (Stott, 2019). Soil organic carbon (SOC) is a major component of soil OM, making up 50% to 60% of its mass but varying across soils and ecosystems (Pribyl, 2010; Roper et al., 2019). Soil carbon can be further fractionated to represent different lengths of time it takes for components to degrade (Roper et al., 2019). Monitoring soil carbon fractions can show its ability to sequester carbon which can help improve other soil attributes (Dalal et al., 2011). Physical soil properties affect how roots, nutrients, and water move through a soil, as well as its ability to resist erosive forces (Hamblin, 1986). Evaluating properties such as penetration resistance (PR) and aggregate stability gives insight on how management practices and soil mineralogy affect erosion and water movement within a soil (Arshad & Coen, 1992; Wolkowski, 1990; Barthes & Roose, 2002). Biological soil properties such as microbial biomass carbon (MBC) are used to measure soil microbial activity and nutrient turnover within the system (Smith et al., 2016; Singh & Gupta, 2018; Chen et al., 2019). While a soil health indicator measures a specific attribute of the soil, indicators are often interrelated and affect how the soil ecosystem functions (Jastrow et al., 2007; Stott, 2019; Stock & Downes, 2008; Dahal et al., 2021). Evaluating a suite of soil health indicators that each reflect certain soil processes allows investigators to take a holistic approach at determining a soil's ability to continue to serve as a functioning ecosystem.

Integrated crop-livestock (ICL) systems have existed since the advent of agriculture, where humans raised livestock for draft power and consumption. Integrated crop-livestock systems were common until the twentieth century, when technological advancements and specialization of agricultural production led to more concentrated crop and livestock production (Hillimire, 2011). Grazing cover crops allows for diversification of farming operations and may improve sustainability of farming operations by adding OM back to the soil, improving nutrient cycling, and making use of residues on the soil surface (Russelle et al., 2017, Kumar et al., 2019). Though ICL systems vary in how they operate, long growing seasons and mild winters of the Southeast allow for establishment of high biomass cover crops in the fall that can be grazed through the winter when other forages are dormant (Schomberg et al., 2021). Many producers in the Southeast have livestock and crops, so there is potential to implement winter grazing of cover crops. Research focusing on maximizing both crop yield and livestock production while maintaining soil health in grazed cover crop systems is minimal. Finding optimal management strategies to maximize forage availability, crop productivity, and soil health is important to improve sustainability of ICL systems. Therefore, the objectives of this study were to 1) evaluate effects of cover crop grazing on soil health indicators in a cotton/peanut rotation under conservation tillage, and 2) determine grazing period lengths to enhance crop production and soil health in the Southeast.

Materials and Methods

Experimental Design

This experiment was conducted at the Wiregrass Research and Extension Center (WREC) in Headland, Alabama. It was initiated in the fall of 2018 and concluded in the fall of 2022. The soil series for the experimental area was a Dothan fine sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudults). Prior to initiation of this experiment, the area was managed in a peanut (*Arachis hypogaea*)- cereal rye (*Secale cereale*)/oat (*Avena sativa*)-pearl millet (*Pennisetum glaucum*) rotation under conventional tillage for more than eight years. The field was split into twelve 0.61-ha paddocks for winter grazing. Paddocks were separated by portable electric fence to maintain cattle in the designated paddocks. The experimental design was a randomized complete block with four grazing treatments replicated three times. The four treatments were 1) a control with no grazing, 2) mid-February cattle removal, 3) mid-March cattle removal, and 4) mid-April cattle removal.

The experimental area was disked, subsoiled, and field cultivated before sowing the first cover crop. The site was managed under a peanut-cotton rotation with the cover crop being sown after cash crop harvest each year. A four-species cover crop mixture of ‘FL401’ cereal rye, ‘Cosaque’ oats, ‘AU Sunrise’ crimson clover (*Trifolium incarnatum*), and ‘T-Raptor’ brassica hybrid (*Brassica* spp.) was sown for each grazing treatment. Seeding rates differed for grazed and non-grazed treatments, with 33.6, 33.6, 16.8, and 3.4 kg ha^{-1} for cereal rye, oat, crimson clover, and brassica, respectively, in non-grazed paddocks and 50.4, 50.4. 18.8, and 3.4 kg ha^{-1} for grazed paddocks per Alabama Cooperative Extension System recommendations (Gamble, 2022, Dillard et al, 2019). Cover crops were sown using a Great Plains 1205 no-till drill (Great Plains Ag, Salina, KS) on 19.05 cm row spacing. Phosphorus, potassium, and soil pH were amended as needed based on soil test recommendations from the Alabama Agricultural Experiment Station (Mitchell, 2012). Nitrogen was applied at different rates for grazed and non-grazed plots, 67.2 kg ha^{-1} for grazed and 26.9 kg ha^{-1} for non-grazed plots, based on different recommendations for small grain cover crops and grazed winter annuals (Mitchell, 2012).

Stocker cattle approximately seven to eight months in age and 266 kg^{-1} at initiation of grazing were used. The target forage allowance was 1 kg of forage dry matter biomass to 1 kg of animal body weight. Cattle were removed from paddocks to allow for regrowth and added back when sufficient forage was available. The goal was to maintain forage height at approximately 15 cm during grazing. Grazing began in early January each year and was terminated by removing cattle when forage biomass was depleted at the designated removal date for each paddock. Cattle had free choice access to water and a high magnesium mineral during the grazing period.

Cover crops in all treatments were terminated approximately two weeks before planting of the cash crop with an application of 1.25 kg ai ha^{-1} of glyphosate for burndown and 1.6 kg ai ha^{-1} of pendimethalin for preemergence activity. Tillage operations consisted of non-inversion subsoiling underneath the cash crop row each season from 2018 to 2022. Both cotton and peanuts were planted using a John Deere 1700 Max Emerge Plus (Deere & Company, Moline, IL) 4 row planter on 91.4 cm row spacings. Peanut variety ‘GA-06G’ was planted in 2020 and ‘AU-NPL17’ was planted in 2022 at 6.8 seeds m^{-1}. Cotton variety ‘Deltapine 1518’ was planted in 2019 and ‘Phytogen 500 W3FE’ was planted in 2021 at 2.4 seeds m^{-1}. A 12.2 x 12.2 meter area was harvested from each sampling point to obtain yield for the cash crop. All pest scouting and management was done according to recommendations from the Alabama Cooperative

Extension System (Smith et al., 2023; Mujumdar et al., 2023). Dates for planting, sampling, and harvest are presented in Table 2-1.

Soil and Plant Sampling

Each replicated plot had two sampling points to encompass the variability of soil texture in each plot. Each sampling point had a marked GPS coordinate to ensure sampling in a consistent location for all years of this study. All soil samples were collected two to four weeks after cover crop termination each year. Ten subsamples were collected at each sampling point with bucket augers at depths of 0-5, 5-10, 10-15, and 15-30 cm for SOC, permanganate oxidizable carbon (POXC), and water stable aggregates (WSA) analyses. A composite sample from 0-15 cm was collected, placed into coolers in the field, and transferred to a refrigerator as soon as possible for microbial biomass carbon (MBC) and soil respiration (CO_2-C) analysis.

Cover crop biomass samples were taken after cattle removal from the last grazing treatment and directly before termination of the cover crop. Four, 0.25-m^2 samples were taken to make a composite sample at each sampling point. Cover crop biomass was oven dried to constant mass and dry weights were obtained.

Root samples for arbuscular mycorrhizal fungi (AMF) colonization were collected from cotton when it reached the fourth true leaf stage and for peanuts at 60 days after planting (DAP). Root systems from five plants at each sampling point were collected. Roots were kept on ice and transported to the lab to be washed. Once washed, larger feeder roots from each root system were clipped off using scissors and tweezers. Roots were placed into a vial containing a 0.5 M formalin acetic acid alcohol (FAA) solution for preservation and storage. Samples were kept in a refrigerator until further analysis could be done.

Soil Organic Carbon

All soil samples were run through a 2-mm sieve prior to lab analyses. A subsample of each sample was ground with coffee grinders for SOC analysis. Soil organic carbon was measured by dry combustion with a LECO CN 828 analyzer (LECO Corporation, St. Joseph, MI) (Nelson & Sommers, 1996). It was assumed no inorganic carbon was present in the soil, and total carbon represents SOC.

Permanganate Oxidizable Carbon

Permanganate oxidizable carbon was measured using the procedure from Weil et al. (2003). Potassium permanganate ($KMnO_4$) is used as an oxidizer in this process which converts the Mn (VII) to Mn (II) as the active C reacts with the $KMnO_4$. A 2.5-g subsample of the air-dried soil sample, 2 mL of a 0.2 M potassium permanganate stock solution, and 18 mL of distilled water were placed in a 50 mL centrifuge tube. These samples were placed on a shaker and shaken for 2 min at 240 oscillations per min. Samples were then taken off the shaker, swirled to ensure all soil was in solution, and placed in a dark area for 10 min to settle. A second set of centrifuge tubes containing 49.5 mL of distilled water were prepared during this time. After 10 min, 0.5 mL of the supernatant in the first tube was drawn out and added to the second tube. The second centrifuge tube was inverted several times to mix the distilled water and supernatant. A set of standard solutions with a 0.005 M, 0.01 M, 0.015 M, and 0.02 M concentration of $KMnO_4$ were made to create a standard curve to calculate the concentrations of active C in the samples. A 0.25-mL sample from the second centrifuge tube and each of the standard solutions was placed on a 96-well microplate with one replication. The microplates were placed on a spectrophotometric microplate reader (Biotek MQX200, Winooski, Vermont) and absorbance was recorded at 550nm. The absorbance of the unknowns was calculated using the equation below where *a* is intercept of the standard curve, *b* is the slope of the standard curve, *Abs* is the absorbance of the sample, 9000 is the milligrams of carbon oxidized by one mole of MnO_4 from Mn (VII) to Mn(II), and *kg* is weight of soil used in the experiment (Weil et al, 2003; Culman et al, 2017).

$$POXC\ \frac{mg}{kg} = \left(0.02\,\frac{mol}{L} - (a + b * Abs)\right) * \left(9000\ mg\,\frac{C}{mol}\right) * \left(\frac{0.02\ L\ solution}{kg\ soil}\right)$$

Water Stable Aggregates

Water stable aggregates were measured using the procedure described in Kemper and Rosenau (1986). A portion of each air-dried soil sample was sieved on a 1-2 mm sieve and a 4-g sample of what remained on top of the sieve was used for analysis. These samples were placed into cups with a 24-cm mesh wire in the bottom and rewetted using a household humidifier to bring them back to near field capacity. Tins were weighed and then filled with DI water and placed on a platform. The samples were then placed on a machine that uniformly raised and lowered them into the tins 35 times per minute for three minutes. Tins were then removed and replaced with tins that contained DI water and 5 mL of diluted sodium hexametaphosphate $[(NaPO_3)_6]$ dispersal solution and the samples were raised and lowered into the solution at the same rate to break down remaining aggregates. Tins were dried in an oven at 105 °C along with a $Na(PO_3)_6$ blank and the weight of the containers was obtained. Weights of both containers were used to find percent WSA, with adjustments being made for the dispersal solution.

Penetration Resistance

Soil penetration resistance (PR) was measured at each sampling location across the field one in mid-June of each year. A tractor mounted, five-probe penetrometer was used to obtain cone-index values down to a depth of 50 cm as described in Raper et al. (1999). The center of the probe was positioned directly over the cash crop row. Two probes were located 22.5 and 45 cm from the center probe on both sides. The machine was positioned so two probes were in a trafficked row middle and two were in an untrafficked row middle. Data was simplified by calculating the area under the curve (AUC) cone index value across all row positions and depths to using the methods described in Balkcom et al., (2016). The equation below was used to calculate the $AUC_{C.I.}$, where i represents the row position, CI_i represents the average cone index value of each row position, d_i represents the distance between row position measures, and k is the total number of row positions (Balkcom et al., 2016). Gravimetric soil moisture content was also obtained at the time of sampling by taking 10 soil samples at the 0-15 and 15-30 cm depths and oven drying at 105 C° for 48 hours. Soil moisture data was to analyzed with PR data for comparison and correlation.

$$AUC_{C.I} = \sum_{i=1}^{k-1} = \frac{[CI_{(i+1)}+CI_i]d_i}{2}$$

Microbial Biomass Carbon and Soil Respiration

Microbial biomass carbon was analyzed using the chloroform fumigation-incubation method described in Jenkinson and Powlson (1976). Field moist samples were sieved to 4 mm. A 4- to 5- g subsample was weighed and placed in an oven at 105 °C for at least 48 h and weighed again to determine soil moisture. Water holding capacity was determined during the first year of the experiment. The weight of moist soil that is required to obtain 25 g of soil on a dry weight basis was then calculated. The weight of moist soil equal to 25 g of dry soil was weighed and placed in a weighed 150 mL-beaker and brought to 50% water holding capacity. Each sampling site had two beakers to be fumigated, one to remain unfumigated, and six blanks were included in the experiment that contained no soil. Each beaker was placed into a mason jar containing approximately 1.5 mL of distilled water and the lid was screwed on tightly to maintain 100% humidity. These jars were placed in a dark room at 25° C for 5 days to incubate before fumigation in a desiccator. A desiccator was cleaned, and two moist paper towels were placed around the edges of the desiccator to maintain humidity within the desiccator. A 150-mL beaker containing approximately 20 boiling chips and 40 mL of ethanol-free chloroform and beakers from the mason jars were placed into the desiccator. The lid was then placed on the desiccator and hooked to a vacuum pump. A vacuum was created within the desiccator until the chloroform boiled for 30 sec and then the vacuum seal was broken. This process was repeated two more times, allowing chloroform to boil for 30 sec the second time and two minutes the third time. After the third fumigation, the neck of the desiccator was closed to trap air in the desiccator. The desiccators were then allowed to incubate with the fumigant for 24 h in a dark area. After 24 h, the vacuum seal was broken, and the wet paper towels were replaced. The lid was placed back on the desiccator and the air was extracted six times for three minutes each, venting the desiccator to the atmosphere after each three-minute interval to remove all chloroform from the samples. The beakers were adjusted to 50% WHC if any change had occurred and placed back into the mason jars. A vial with 5 mL of 1.0 M NaOH was also placed in the beaker for a CO_2 trap and the lids were closed tightly on the jars. The jars were then placed in a dark place and kept around 25°C for ten days to incubate. On the tenth day of incubation the NaOH trap was titrated to evaluate the amount of CO_2 released from the respiration of the microbial biomass. The vials of NaOH were transferred to a 125-mL Erlenmeyer flask and a 2-mL aliquot of 1.5 M $BaCl_2$ was added to the flask to precipitate out carbonate in the solution. Phenolphthalein was added to the solution as an indicator. The solution was then titrated to the end point with 0.25 M HCl. The

CFI process assumes that only 41% of microbial biomass mineralizes in the ten-day incubation period. The equation used to determine the MBC concentration is listed below.

$$\mathrm{MBC}\left(\frac{\mu\mathrm{g}}{\mathrm{g\ soil}}\right) = \frac{\left(\mathrm{HCl\ used\ in\ blank\ }(\mu\mathrm{L}) - \mathrm{HCl\ used\ in\ soil\ }(\mu\mathrm{L})\right) * \frac{\mathrm{HCl\ molarity} * 6}{\mathrm{soil\ dry\ weight}}}{0.41}$$

AMF colonization

Root samples for AMF colonization were analyzed using the acid fuschin staining process used in Berch and Kendrick (1982). Roots were removed from the formaldehyde, alcohol, acetic acid (FAA) solution and washed several times with distilled water in a clean petri dish. Washed roots were placed in labelled test tubes filled with 10% KOH. Test tubes were placed in a hot water bath (90° C) and left there for ~90 minutes or until roots were dark brown in color, showing root tissues have dissociated. Dissociated roots were placed on clean petri dish and rinsed three times with distilled water. Roots were then immersed in lactic acid for three minutes to neutralize the KOH. Roots were then transferred to a clean microscope slide and 0.5% acid fuschin stain was added. The slides were heated three times until it started to smoke to ensure staining of the AMF. Roots were washed with liberal amounts lactic acid glycerol until pinkish tint of the root dissipated. Two to three sections of stained roots were placed on a clean slide with lactic acid glycerol and a cover slip was placed carefully on them. Microscope slides was placed under a compound microscope on the 16x lens. Fifty eye shots were taken from roots at each sampling location by starting on one of the roots and moving an equal distance between each eye shot. Each eye shot was assigned a measure of “AMF present” or “AMF not present” based on absence or presence of AMF mycelium or vesicles. The percent AMF colonization was determined by dividing the “AMF present” eye shots by the total number of eye shots.

Data analysis

POXC, WSA, SOC, soil moisture, and Melich (P, K, Mg and Ca) data were subjected to mixed model repeated measures analysis of variance using PROC GLIMMIX in SAS Version 9.4 (SAS Institute Inc., Cary, NC). Treatment, year, depth, and their interaction were used as fixed effects and replication within year and treatment within replication and year were used as random effects. The first order antedependence structure ANTE(1) was used to account for repeated measures among the four sampling depths (2.5, 7.5, 12.5 and 22.5 cm). MBC and CO_2-C were subjected to mixed model repeated measures analysis of variance. The first order autoregressive structure AR(1) was used to account for repeated measures among years (2019, 2020, 2021 and 2022). Biomass, AUC, AMF, peanut data were analyzed using year, treatment and their interaction as fixed effects. Replication within year and treatment within replication and year were used as random effects. For cotton yield data specifically, 2019 data were exported from a combine spatial dataset, aggregated for each treatment and replication, and merged with 2021 data. Due to aggregation, there was one observation for each treatment within each replication (no subsamples) and therefore, replication within year and treatment within year were used as random effects. For all analysis, degrees of freedom were calculated using the Kenward-Rodger method and Tukey adjustment was used to adjust for multiple comparisons (Littell et al., 2006).

Results and Discussion

Environmental Conditions

Average monthly temperatures did not fluctuate much from year to year. Slightly warmer temperatures were observed in the spring of 2020 compared to the other years. The average mean temperature in this region was 19.6° C across the four years. Precipitation distribution varied from year to year. Average rainfall was 102.7 cm in 2019, 120.2 cm in 2020, 128.3 cm in 2021, and 83.9 cm in 2022. Thirty-year-averages for precipitation and temperature along with average monthly temperatures and total monthly precipitation from each year of the study are depicted in Fig. 2-1.

Cover Crop Biomass

Cover crop biomass was influenced by year, treatment, and their interaction (Table 2-2). The non-grazed control sustained greater biomass at termination compared to the mid-February, mid-March, and mid-April treatments averaged across the years of the study (Table 2-3). Additional treatment differences varied according to growing season, and weather conditions were likely a driving factor for these differences. For example, in 2020 the mid-February treatment produced a statistically greater amount of biomass than the mid-April treatment; however, in 2021, under drier conditions in the spring the two treatments were not significantly different from each other. Drier winters and springs along with grazing may have caused slower regrowth of the cover crops, producing less biomass for grazed treatments in 2021 and 2022. Ample time, moisture, and warmer temperatures are needed to support growth of cover crops (Strock et al., 2004; Schomberg et al., 2006; Keene et al., 2017). Differences in cattle removal dates between years may have contributed to the differences in biomass production as a result of varying amounts of time being allowed for recovery and regrowth. For example, cattle were not added back to the mid-April grazing treatments at the end of the 2021 season because biomass production was too low to justify adding cattle back to the system. This period allowed more time for regrowth and biomass accumulation than the mid-March treatment.

Treatment differences in biomass remaining at cover crop termination were expected due to different grazing intensities. When examining treatment differences across years, the non-grazed control had the highest biomass remaining at termination followed by the mid-February removal date. The significantly higher levels of biomass in the non-grazed control were anticipated since no biomass was removed with grazing. Similarly, the mid-February treatment was higher than the mid-March and mid-April treatment because it had more time for regrowth. The mid-March and mid-April treatments had similar levels of remaining biomass at termination, but the mid-April treatment is numerically lower because livestock were able to consume cover crop biomass for a longer period. (Table 2-3). Cover crop biomass production in 2022 was significantly lower than in 2019 and 2020 and 2021 did not differ statistically from any year. Differences between years may be due to a combination of weather conditions, soil moisture, and pest pressures. Lower precipitation in the fall of 2021 and spring of 2022 may have limited biomass production and regrowth (Fig. 2-1). Ample precipitation during establishment of the cover crop in 2018 and slightly warmer temperatures in February 2019 may be contributing factors to the increased biomass during this year.

Soil Organic Carbon

Soil organic carbon was influenced by treatment, depth, and the interaction of year with depth (Table 2-2). Deeper sampling depths exhibited stratification of SOC, with concentrations decreasing with depth (Fig. 2-2). Longer grazing periods tended to show lower buildup of SOC, with the mid-April treatment being lower than the non-grazed treatment (Fig. 2-3). Soil organic carbon content is dynamic and can be affected by factors including climate, soil type, soil mineralogy, topography, vegetation, and various other biotic and abiotic factors (Lal, 2016; Feng et al., 2013). The southeastern United States has a warm, humid climate and sandy textured soils, which lead to more rapid degradation of OM and slows the buildup of SOC (Franzluebbers, 2005; Bronick & Lal, 2005).

Soil organic carbon accumulation and stratification was likely affected by tillage operations. Prior to this experiment, the area had been managed under a conventional tillage system, which allowed OM to be oxidized easier. The area was converted to conservation tillage at initiation of the current study (i.e., 2018), and less soil disturbance allowed for more SOC to accumulate near the surface. Numerous studies have found that conservation tillage allows for accumulation and protection of SOC because what is assimilated into the soil is protected from oxidation (Wood et al., 1992; Varvel & Wilhelm, 2010). Stratification of SOC increased over time, with the difference between the shallowest and deepest depth growing over time (Fig. 2-2). While stratification of SOC increased with time, SOC at each depth did not differ from each other across years. Levels of SOC remained numerically similar at deeper depths. The lack of surface tillage and mixing of crop residues likely caused a higher accumulation of SOC near the soil surface, mirroring trends from similar studies (Deiss et al., 2021, Causarano et al., 2008, Farmaha et al., 2022).

Interestingly, SOC was affected by grazing treatment, but differences did not vary with depth (Fig. 2-2). Cover crop biomass additions to the system can help build SOC due to both aboveground residues being broken down and mixed into the soil by tillage, leaching, or microorganism activity (Lacey et al., 2020). Belowground residues can also contribute to SOC, since the levels of belowground biomass can represent 30 to 50% of the total biomass produced by a cover crop, but belowground biomass was not quantified in this study (Sainju et al., 2006; Ruis et al., 2020). Intensively grazed treatments left less cover crop biomass to be incorporated into the soil profile, but ~25% of the carbon consumed by the cattle is returned back to the system through manure which could offset some of the plant biomass removal (Parsons et al., 2009). The most intense grazing treatment had significantly lower SOC compared to the non-grazed control, showing that cover crop residue removal affects SOC concentrations. Little work has focused on effects of ICL systems on SOC in the Southeast, but a study from Georgia found that cover crops and grazing had little effect on SOC stocks in the soil down to 30 cm after 3 years (Franzluebbers & Stuedemann, 2008a).

Mixed reviews have been published on overall effects of cover crops on SOC in sandy textured soils of the southeastern United States. Sainju et al. (2002) found that cover crops did not increase SOC over the 0-20 cm depth after 6 years but did not allow it to decrease compared to the conventionally tilled control. Similarly, Decker et al., (2022) found no changes in SOC for a loamy sand soil from 0-30 cm with cover crops after 4 years in south Alabama. A review by Causarano et al. (2006) found that SOC was generally increased by cover crop practices across the Southeast over an average of approximately 10 years, so incorporating cover crops into a cropping system under some soil types and climates may help build SOC over longer periods of time. Studies conducted on silt loam textured soils found that cover crops had limited effects on SOC (Rorick & Kladivko, 2017; Eckert, 1991, Chu et al., 2017). Studies focusing on SOC changes under cover crop grazing are limited, but some previous research conducted shows that grazing has limited positive or negative effects on SOC. One study in Nebraska found that SOC showed no change from the 0-20 cm depth under grazing to 50% biomass remaining and non-grazed treatments (Singh et al., 2022). Franzluebbers et al., (2008) found that treatments where grazing removed 90% of the biomass SOC was lower in the top 6-cm of the soil compared to the non-grazed after two years. Results from this study also show that SOC was higher in the non-grazed compared to the mid-April treatment where a majority of the biomass was removed (Fig. 2-3).

Permanganate Oxidizable Carbon

Permanganate oxidizable carbon is an active carbon fraction that can be decomposed readily by soil microorganisms. There was no influence of grazing treatment on POXC. However, POXC was influenced by year, depth, and their interaction (Table 2-2). The lack of treatment effect on POXC suggests that more intensive grazing does not have a positive or negative effect on labile carbon stocks in the soil. A three-year study in West Texas found that grazing did not affect POXC levels, aligning with the results from this study (Mubvumba et al., 2021).

The year by depth interaction showed that POXC levels at the 15-30 cm depth decreased after 2019 (Fig. 2-4). The system was converted to conservation tillage management at the start of this study, which could cause a decrease in POXC at deeper depths over time since it oxidizes more readily and the soil is not being turned to replace it (Culman et al., 2012). Plaza-Bonilla et al., (2014) found that POXC increased in the 0-5 cm depth but decreased over time in the 5-20 cm and 20-40 cm depths when a field was switched to conservation tillage, similar to findings of this study at deeper depths. Switching this area from intense forage and peanut production to include cotton may have also contributed to this decrease since cotton adds little biomass back to the soil (Causarano et al., 2006). In 2020, POXC levels were lower at the 0-5 and 15-30 cm soil depths. Soil sampling in 2020 occured closer to cover crop termination than in 2019 and cover crop biomass production was numerically lower in 2020 compared to 2019 and 2022 which may have led to differences in POXC concentrations and degradation rates that year.

Both 2020 and 2022 had lower POXC values than values first observed for this study in 2019 (data not shown). This is inconsistent with other studies (Ghimire et al., 2019, Mubvumba et al., 2021) that have found cover crops increase POXC over time. The loamy sand soil texture of this location in the southern Coastal Plain may be the limiting factor for POXC accumulation. Other studies conducted on similar soil types found, Johnson et al., (2021), that cover crops did not affect POXC, while studies on soils with heavier clay content, Ghimire et al., (2019), found cover crops to positively increase POXC. Lucas & Weil (2012) also found that changes in POXC were lower for coarser textured soils compared to finer textured soils. Permanganate oxidizable carbon may decompose quickly in this environment, also making accumulation hard to achieve. Long term practices may influence other soil properties that aid the soil in retaining POXC, so longer studies may need to be conducted to observe differences.

Since POXC is a fraction of SOC in the soil, a correlation analysis was performed. Permanganate oxidizable carbon is moderately correlated with SOC (Table 2-5). Other studies have observed that POXC is highly correlated with SOC under some management conditions and less correlated in others, finding it to not always be the most sensitive measure of soil health changes (Plaza-Bonilla et al., 2014; Duval et al., 2018; Lucas & Weil, 2012), These other studies were conducted on soil types with higher clay contents which may protect POXC better than the loamy sand soil texture at this location. Studies that incorporated some sort of soil disturbance (Plaza-Bonilla et al., 2014), found that POXC was less correlated with SOC under these conditions. A slightly positive correlation was also observed for MBC and WSA, but the correlation was weak. Other studies have found that MBC and WSA are weakly correlated with POXC (Culman et al., 2012; Lussier et al., 2020).

Penetration Resistance

Penetration resistance, a measure of the capacity of a soil to withstand downward force, was influenced by grazing treatment and year. The non-grazed control was numerically lower than all grazed treatments, and the mid-April grazing treatment was significantly higher than the non-grazed treatment (Table 2-2, 2-4). Longer grazing periods were expected to increase soil PR because the force exerted by a cow's hoof impact is 0.3 to 0.7 Mpa, which is higher than the force exerted by some agricultural vehicles (Cohron, 1971; Lipiec & Simota, 1994; Lipiec et al., 2002). The higher traffic across the mid-April cattle removal treatments lead to more PR due to increased animal traffic. Other studies have observed mixed results on PR due to cover crop grazing. Blanco-Canqui et al., (2020) found that grazing cover crops for three years on a sandy loam in Nebraska only increased PR significantly in an intensively grazed system in one out of three years compared to a non-grazed control. This could be due to different levels of precipitation during the growing seasons and the freeze/ thaw that occurs in northern regions of the United States in the winter that can alleviate PR. Franzluebbers & Stuedemann, (2008) found that grazing cattle on winter annuals in an ICL system significantly increased PR near the soil surface after 2.5 years on a sandy loam soil in Georgia.

The lack of difference between non-grazed, mid-February, and mid-March treatments may be due to in-row subsoiling that breaks up compacted layers below the row to allow for root growth and this may have alleviated some compaction in all plots. The penetration resistance increased below 30 cm in all treatments, which is approximately the depth of the subsoiler operation (Fig. 2-7). Penetration resistance increased at shallower depths in the mid-April treatment, showing that subsoiling did not alleviate as much compaction as it did in the other treatments (Fig. 2-7). Tollner et al., (1990) found that deep tillage beneath the crop row alleviates compaction in grazed lands to help with crop growth. Lower stocking rates can also ameliorate effects of grazing on PR, as da Silva et al. (2003) found that lower stocking rates had less increase in PR from grazing. Stocking rates in this experiment along with cattle removal when forage levels were low may have contributed to similar results for the mid-February and mid-March treatments. Correlation analyses showed that both soil moisture had a significant but weak, negative correlation with penetration resistance (Table 2-6). Several other studies have found that penetration resistance was significantly correlated with soil moisture content (Vaz et al., 2011; Vaz et al., 2013; Imhoff et al., 2016). Penetration resistance is increased by decreased soil moisture because there is more friction between the soil particles and penetrometer. The increase in PR could be due to a combination of compacted soil particles and decreased soil moisture.

Penetration resistance is also influenced by the water content of the soil. Soil moisture content at the time of PR sampling decreased with increased grazing (Table 2-4). The non-grazed control had significantly higher soil moisture compared to the mid-March and mid-April grazing removal treatments at the 0-15 and 15-30 cm depths. The mid-April treatment was also significantly lower than the mid-February treatment at the 0-15 cm depth. Differences in soil moisture content can be explained by the amount of residue left on the soil surface at the time of sampling. Images in Figure 2-8 show the difference in residue amounts remaining during the peanut growing season, with limited cover in the mid-April cattle removal treatment. Cover crops can help preserve soil moisture by shading the ground from solar radiation to reduce evapotranspiration, adding OM to the system, slowing movement of water across the soil surface, and increasing infiltration (Williams & Weil, 2004; Acharya et al., 2019; Blanco-Canqui et al., 2015). Increased cover crop residue on the soil surface in the non-grazed control likely contributed to differences in soil moisture content, which is similar to findings of other studies (Clark et al., 1997; Basche et al., 2016; Teasdale & Mohler, 1993).

Water Stable Aggregates

Water stable aggregates were influenced by depth, year, and treatment, but not by any interactions between the three (Table 2-2). The non-grazed treatment was significantly higher than the mid-March and mid-April treatments (Table 2-4). While there was a significant difference between treatments, WSA was high in all treatments with a range of 91.9 to 89.8%, The upper 5 cm of the soil had significantly lower WSA than the other soil depths. Water stable aggregates were higher in 2019 than the other three years of the study (data not shown).

Other studies have also found ICL systems to have some to no effect on WSA. Franzluebbers & Stuedemann (2008b) found that grazing had little effects on WSA with a decrease of only 0.06 g g^{-1} being observed at the 3-6 cm depth, 2.5 years after project initiation in a Cecil sandy loam soil in Georgia where 90% of the cover crop biomass was removed by grazing over the non-grazed control. No net change was observed in WSA at the end of a 13-year study in the portion managed as a cropping system with winter grazing (Fultz et al., 2013). The slight decrease in aggregate stability in this study by treatment could be due to soil surface disturbance by grazing and less additions of crop residues into the soil. Changes in OM levels or compositions may also influence WSA at all depths in the soil (Tisdall & Oades, 1982). Organic matter additions in the grazing system included manure and less plant residues so the OM in this system may interact with soil particles differently. Switching the system to conservation tillage stratifies the OM deposition, but also protects aggregates that have formed deeper in the soil profile. This along with more clay content deeper in the soil profile most likely led to the higher

WSA at deeper depths. Weak correlations between WSA, POXC, and cover crop biomass were significant (Table 2-5). Water stable aggregates could be affected by POXC because this labile form of carbon may be the binding agent in many of the soil aggregates (Chan et al., 2002).

Microbial Biomass Carbon

Cover crop grazing did not influence MBC by year or treatment (Table 2-2). Soil microbial biomass ranged from 253 to 228 µg g^{-1} across treatments. Soil MBC is affected by a variety of factors such as climate, soil type, and both the amount and quality of biomass present (Singh & Gupta, 2018). Differences in aboveground cover crop biomass remaining on the soil surface did not cause a change in the MBC in the soil. The change in aboveground cover crop biomass may have been offset by deposition of OM in the form of manure which also provides a labile food source for microbes. The lack of difference in MBC may have also been due to lack of aboveground biomass contributions to MBC at the time of sampling. Austin et al., (2017) found that belowground cover crop biomass (roots) contributed more to MBC in the short term after termination than aboveground biomass does. Austin et al., (2017) also found that approximately the same amount of cover crop biomass is present both above and below ground.

Other studies involving ICL systems have found mixed results concerning MBC. A study from Illinois found that MBC increased in grazed plots in one out of three years of an ICL system and a study in North Florida found that MBC was significantly higher in grazed plots in the non-irrigated sections, but not under irrigated sections (Tracy & Zhang, 2008; George et al., 2013). Franzluebbers & Stuedemann, (2015) found that grazing did not affect MBC over a 7-year study in Georgia. Other studies may have found some differences in MBC due to type of extraction method, climate, grazing and cover crop management, and sampling time. The lack of change in MBC suggests that grazing does not have a negative effect on MBC in the soil.

CO_2 respiration

No treatment by year or treatment effect was observed for CO_2 respiration, but a year effect was observed (Table 2-2). CO_2 respiration ranged from 54.3 to 61.9 μg g^{-1} across treatments for the 0-15 cm depth. CO_2 respiration was higher in the later years of the study than in the first two. This could be due to increased stratification of SOC as several other studies have observed increased SOC from cover crop residue also increases soil CO_2 respiration (Singh & Kumar, 2021; Hurisso et al., 2016). CO_2 respiration is related to microbial activity in the soil, and MBC had a moderate, significant correlation in this study with CO_2 respiration. This is consistent with other studies where a significant correlation was made between MBC and soil respiration (Farmaha et al., 2022).

Arbuscular Mycorrhizal Fungi Colonization

Grazing treatments influenced AMF colonization for peanuts, but not for cotton (Table 2-2). Mean percent AMF colonization across years for both crops are displayed in Table 2-6. Arbuscular mycorrhizal fungi colonization of both cash crops was ~70% in all years of the study. While data for peanut AMF colonization was significant, there was not a large numerical change. Arbuscular mycorrhizal fungi are an underground fungal network that forms symbiotic relationships with plants. Three of the four cover crop species (i.e., rye, oats, and crimson clover) used in this study can be associated with AMF, but forage radish does not because species in the Brassicaceae family cannot form associations with AMF (Hill, 2006; Bowles et al., 2016). Although radishes were included in the mixture, the other species provided living roots for AMF to infect and allow it to continue to grow in the soil. Keeping a living host in the soil for longer periods of time provides AMF with carbon sources needed for energy. A meta-analysis by Bowles et al., (2016) found that winter legume cover crops increased AMF colonization of the cash crop by 30%. While this study did not include a fallow for comparison, colonization rates in this study were similar to results found in other studies evaluating AMF colonization for row crops, including peanuts, with a range of 30 to 80% (Bowles et al., 2016; Carrenho et al., 2007; Kabir et al., 1997; He et al., 2017; & White & Weil, 2009). A limited number of ICL system studies have evaluated AMF colonization, finding that there was not a significant effect on AMF colonization from grazing cover crops in an ICL system (Sekeran et al., 2021; Davinic et al., 2013). Klumpp et al., (2009) found that increased grazing in a perennial system resulted in lower AMF populations due to smaller root systems. This study differs because this system was maintained in an annual rotation. The diverse, annual cropping system of this study may have mitigated any negative effect that grazing may have on AMF colonization.

Mehlich-1 extractable nutrients

No treatment effect was observed for Mehlich-1 extractable phosphorus, potassium, calcium, or magnesium levels in the soil, but significant differences were observed for all four nutrients by year and depth. The lack of treatment effect shows that removal of biomass and additions of cattle manure did not affect levels of extractable nutrients. While no differences in nutrient levels were found for different grazing periods in this study, others have found that moderate grazing could potentially affect some extractable nutrient levels in the system. A study in Brazil found that moderate grazing (30-40 cm of biomass remaining) of an Italian ryegrass and black oat cover crop in rotation with soybeans led increases in available calcium by ~1.5 and 5.8 mg kg^{-1} and ~3.7 and 1.1 mg kg^{-1} for magnesium when 30 and 40 cm of residue were left remaining in grazing treatments compared to the non-grazed plot (Assmann et al., 2017). Most nutrients consumed by cattle are released back into the system through manure, and a large portion of phosphorus and potassium in manure is plant available (Eghball et al., 2002; Martens

& Entz, 2011; Schoenau & Davis, 2006). While nutrients are recycled from manure deposition in grazed paddocks, nutrients are also returned to the system in the form of cover crop biomass for non-grazed paddocks. Nutrients contained in cover crop biomass are not available to plants as quickly as those in manure because they must be released by degradation from microbes which depends on the C:N ratio of the biomass.

Levels of extractable nutrients can be affected by different variables in the system. Soil type, soil mineralogy, climate, aspect, soil microbial activity, residue composition, removal in harvested crops, and soil additions and amendments can all influence levels of nutrients held within the system (Stutter et al., 2015; Jacoby et al.; 2017; Tully & Ryals, 2017). Differences observed by year for each nutrient can be explained by application of fertilizers and lime to the field, as recommended from soil test reports from the Auburn University soil testing lab (Mitchell, 2012). Applications of each nutrient were different based on the soil test report for that year. Sampling times may have been closer to the fertilizer application date in some years than others, causing concentrations in the soil to be different. Soil concentration of these four minerals also changed by depth, becoming progressively lower with depth. Cations such as potassium and calcium are bound to soil particles closer to the soil surface in this low CEC soil (Howard et al., 1999). Stratification of nutrients can commonly occur under no-till or conservation tillage (Vyn & Janovicek, 2001), which helps to explain the stratification of nutrients in the soil since this study only incorporates soil mixing when digging peanuts and non-inversion subsoiling.

Crop Yield

A significant treatment effect was observed for cotton yields but not peanut yields (Table 2-2). Yields for peanuts and cotton are found in Fig. 2-5 & 2-6. Treatment differences observed in cotton showed a lower yield in the more intensively grazed plots. The mid-March yields were lower than the control and mid-February, while the mid-April treatments did not differ from any others. Over a 90 kg ha^{-1} difference was observed between treatments across both years. No differences were observed for peanut yield when averaged across both years. While no significant differences were observed, a 192 and 254 kg ha^{-1} difference was observed between the highest and lowest yielding plots in 2020 and 2022.

Other studies have found mixed results on the effect of cover crop grazing on crop yields. A study in South Dakota found that grazing cover crops to remove approximately 20% of available biomass did not have a significant effect on corn yield, but a 17% decrease in corn yield was observed in 1 out of 4 years compared to the control (Rai et al., 2021). Rai et al., (2021) also found there were no significant differences in profit between the two systems. Hill et al. (2004) found no significant differences in peanut or cotton yields when planted following an 84-day grazing period of a ryegrass/ cereal rye cover crop mixture in Georgia. A study in the High Plains of Texas found that wheat grazed to the soil surface and non-grazed treatments in continuous cotton produced similar cotton lint yields (Allen et al., 2005) Cover crops can be grazed and pose little threat of yield reduction in the cash crop, but not in all climates and environments. A study in the Piedmont of Georgia observed that grazing had variable effects on corn and soybean yields, increasing yields in some years and decreasing them in others (Franzluebbers & Stuedemann, 2014). Grazing management is an important aspect to keep in mind when evaluating effects on crop yields. Studies in which more residue was left on the soil surface had less effect on crop yields compared to those that allowed most of the biomass to be removed (Rai et al., 2021; Franzluebbers & Stuedemann, 2014). Results of this study show treatments that had less biomass remaining on the soil surface had lower yields numerically, but only significantly reduced yields in cotton in the Mid-March treatment. Lower cotton yields in the mid-March treatment may be related to lower water retention with lower cover crop biomass, which can also lead to increased soil penetration resistance (Busscher et al., 1997). Increased penetration resistance reduces growth of plant roots, preventing them from reaching nutrients and water deeper in the soil (Siri-Prieto et al., 2007; Schomberg et al., 2021; Raper et al., 2000). Finding a stocking rate and an optimal amount of biomass that must remain on the surface to reduce the possibility of lower yields under grazing systems is important to improve economic and environmental sustainability of ICL systems.

Conclusion

In the short term (4 years), the ICL system had mixed effects on soil health indicators and crop yields. The lack of differences in POXC, MBC, and extractable nutrients suggests that factors other than grazing may have a greater effect on these soil characteristics in this region. Soil organic carbon was higher in treatments with larger amounts of remaining cover crop biomass, suggesting that residues returned in cattle grazing treatments may be degraded quicker or lost compared to the non-grazed treatments. Treatment differences observed in physical soil health indicators suggest that more intensive grazing of cover crops in this region can lead to some negative effects on soil physical characteristics. Crop colonization of AMF may be influenced by grazing treatments, but AMF had the ability to provide high colonization rates in both crops. Grazing cover crops may lead to the increased potential for lower crop yields but susceptibility to other environmental factors such as drought may also be increased due to lower soil water content in areas with less ground cover. Cover crop grazing in the southeastern United States provides a possibility to diversify agricultural operations in the region but must be managed with care to protect soil health and increase farm productivity. Moderate grazing of cover crops may provide some cover throughout the growing season to improve soil health while improving economic efficiency in ICL systems.

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Figures and Tables

Table 2-1. Dates for field operations and samplings at the Wiregrass Research and Extension Center for 2018-2022.

	Year				
Operation	2018	2019	2020	2021	2022
Cover Crop Planting	29 Oct.	4 Nov.	15 Oct.	3 Nov.	-
Grazing Begins	-	11 Jan.	13 Jan.	4 Jan.	6 Jan.
Mid-Feb. Cattle Removal	-	15 Feb.	12 Feb.	15 Feb.	16 Feb.
Mid-Mar. Cattle Removal	-	15 Mar.	9 Mar.	15 Mar.	21 Mar.
Mid-Apr. Cattle Removal	-	5 Apr.	9 Apr.	15 Mar.	30 Mar.
Cover Crop Termination	-	18 Apr.	14 Apr.	7 Apr.	8 Apr.
Cash Crop Planting	-	30 Apr.	4 May	17 May	3 May
Soil Sampling	-	14 May	1 May	23 Apr.	26 Apr.
Cash Crop Harvest	-	12 Oct.	1 Oct.	15 Oct.	27 Sept.

Table 2-2. Summary of analysis of variance (ANOVA) for aboveground cover crop biomass, soil organic carbon (SOC), permanganate oxidizable carbon (POXC), water stable aggregates (WSA), microbial biomass carbon (MBC), soil respiration (CO_2-C), arbuscular mycorrhizal fungi colonization for peanuts (AMF-P) and cotton (AMF-C), penetration resistance (PR), soil moisture (SM), cotton yield (CY), peanut yield (PY), and Mehlich 1 data for P, K, Ca, Mg (ppm) in response to year (Y), soil depth (D), cover crop grazing treatment (T), and their interactions.

	Interaction (Pr > f)						
	Y	D	T	Y x T	T X D	Y X D	Y x D x T
DF	3	3	3	7	7	7	11
Biomass	0.0294	-	<0.0001	0.0482	-	-	-
SOC	0.8498	0.0001	0.0360	0.9918	0.2872	0.0019	0.9550
POXC	0.0062	0.0001	0.1092	0.411	0.9856	0.0001	0.6285
WSA	0.0003	0.0001	0.0031	0.9849	0.5659	0.4904	0.8977
MBC	0.2421	-	0.6654	0.3615	-	-	-
CO_2-C	0.0074	-	0.518	0.1275	-	-	-
AMF-P	0.4423	-	0.0432	0.0181	-	-	-
AMF-C	0.1747	-	0.9204	0.7344	-	-	-
PR	0.002	-	0.0009	0.7161	-	-	-
SM	0.0124	0.0001	0.0001	0.0681	0.0043	0.0022	0.1585
PY	0.0041	-	0.1752	0.9411	-	-	-
CY	0.2575	-	0.0062	0.1438	-		-
K	0.0001	0.0001	0.3987	0.9922	0.4368	0.1954	0.4151
P	0.0001	0.0001	0.0657	0.9991	0.8038	0.0001	0.9752
Ca	0.0001	0.0001	0.6487	0.9171	0.9478	0.0001	0.192
Mg	0.0001	0.0001	0.5758	0.9972	0.6708	0.0001	0.78

[†]DF- degrees of freedom

Table 2-3. Aboveground cover crop biomass production at termination according to the cattle removal date treatments from 2019 to 2022 at the Wiregrass Research and Extension Center.

Treatment	Cover Crop Biomass Production				
	2019	2020	2021	2022	Mean
	(kg ha^{-1})				
Non-grazed	7600 a	6470 a	7700 a	6590 a	7060 a
Mid-Feb.	4460 ab	3400 ab	2520 b	3490 a	3400 b
Mid-Mar.	2750 b	2270 bc	1500 b	1150 b	1810 c
Mid-Apr.	2090 b	1010 c	1980 b	1080 b	1450 c

[†] Values within a row followed by different letters are statistically different using Tukey's HSD at α=0.05.

Table 2-4. Water stable aggregates (WSA) across the 0-30 cm depths, soil moisture (SM) content from the 0-15 and 15-30 cm depths and means for area under the curve for cone index values of penetration resistance (PR) for the 0-50 cm sampling depth across all years for each cattle removal date treatment at the Wiregrass Research and Extension Center.

	Soil Health Indicators			
Treatment	PR	SM (0-15 cm)	SM (15-30 cm)	WSA
	— Index Value —	%		
Non-grazed	138 a	9.91 a	11.8 a	91.9 a
Mid-Feb.	159 ab	9.10 ab	10.9 ab	90.7 ab
Mid-Mar.	159 ab	8.55 bc	10.2 b	90.0 b
Mid-Apr.	177 b	8.26 c	10.2 b	89.8 b

[†] Values within a column followed by different letters are statistically different using Tukey's HSD at α=0.05.

Table 2-5. Pearson's Correlation Coefficients for cover crop biomass (CCB), permanganate oxidizable carbon (POXC) (0-15 cm), soil organic carbon (SOC) (0-15 cm), water stable aggregates (WSA) (0-15 cm), arbuscular mycorrhizal fungi (AMF) colonization, microbial biomass carbon (MBC), soil respiration (CO_2-C), area under the curve index values for penetration resistance (PR), and soil moisture (%) at time of PR measurements. Coefficients for SM are only listed for biomass and AUC values because they are not insightful to correlate to other soil health indicators due to method of sampling.

	Pearson's Correlation Coefficients								
	CCB	SOC	POXC	WSA	MBC	CO_2-C	AMF	PR	SM
CCB	1.0000	NS	NS	0.2746 **	NS	NS	NS	-0.3582 **	0.4094 ***
SOC		1.0000	0.5627 ***	NS	0.4117 ***	NS	NS	NS	
POXC			1.0000	0.4192 ***	0.3825 ***	NS	NS	NS	
WSA				1.0000	NS	NS	NS	NS	
MBC					1.0000	0.5885 ***	NS	NS	
CO_2-C						1.0000	NS	NS	
AMF							1.0000	NS	
PR								1.0000	-0.2667 **
SM									1.0000

[†]** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
NS, nonsignificant at the 0.05 probability level.

Table 2-6. Values for peanut and cotton arbuscular mycorrhizal fungi (AMF) colonization for each year by cattle removal date treatment at the Wiregrass Research and Extension Center.

	Soil Health Indicator			
	Cotton		Peanut	
Treatment	Year	AMF Colonization	Year	AMF Colonization
		—— % ——		—— % ——
Non-grazed	2019	72.0	2020	73.1 ab
Mid-Feb.	2019	74.7	2020	70.3 ab
Mid-Mar.	2019	74.3	2020	66.7 b
Mid-Apr.	2019	71.7	2020	72.7 ab
Non-grazed	2021	67.0	2022	67.7 b
Mid-Feb.	2021	68.3	2022	77.3 a
Mid-Mar.	2021	67.0	2022	71.0 ab
Mid-Apr.	2021	71.3	2022	73.5 ab

[†] Values followed by the same letter are not significantly different from others under the same crop at $\alpha = 0.05$ with Tukey's HSD.

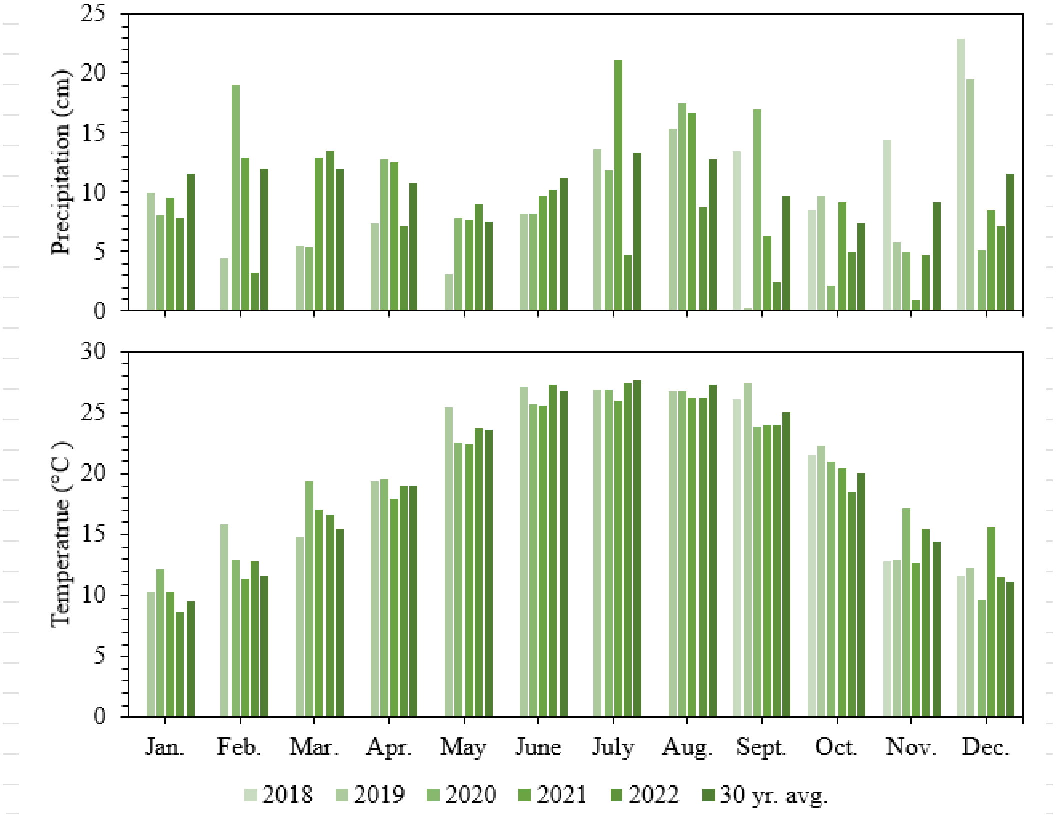

Figure 2-1. Total monthly precipitation and monthly average temperatures for 2019, 2020, 2021, 2022, and the 30-year average at the Wiregrass Research and Extension Center.

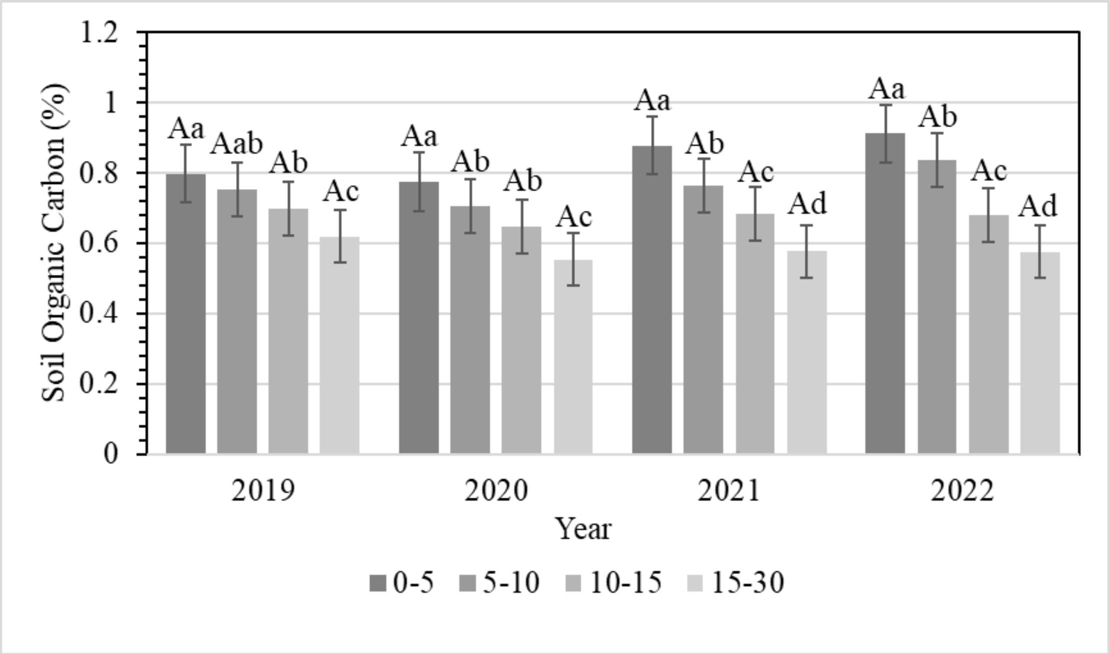

Figure 2-2. Values for soil organic carbon (SOC) means by year and depth. Values followed by the same lowercase letters are not significantly different from other values for depth within that year and values followed by the same uppercase letters are not significantly different from other values for year within a depth at α=0.05 using Tukey's HSD.

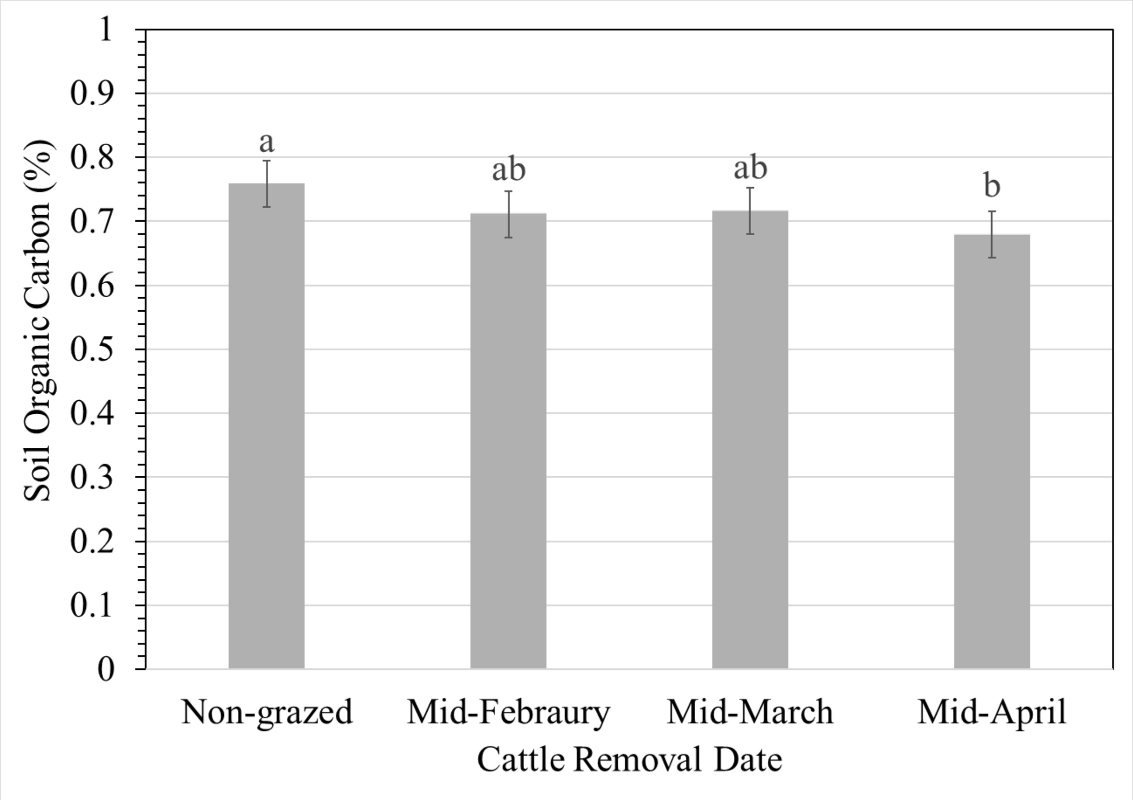

Figure 2-3. Soil organic carbon (SOC) according averaged across all years for the 0-30 cm depth according to cattle removal treatment. Treatments labeled with the same letters are not significantly different from each other at α = 0.05 using Tukey’s HSD.

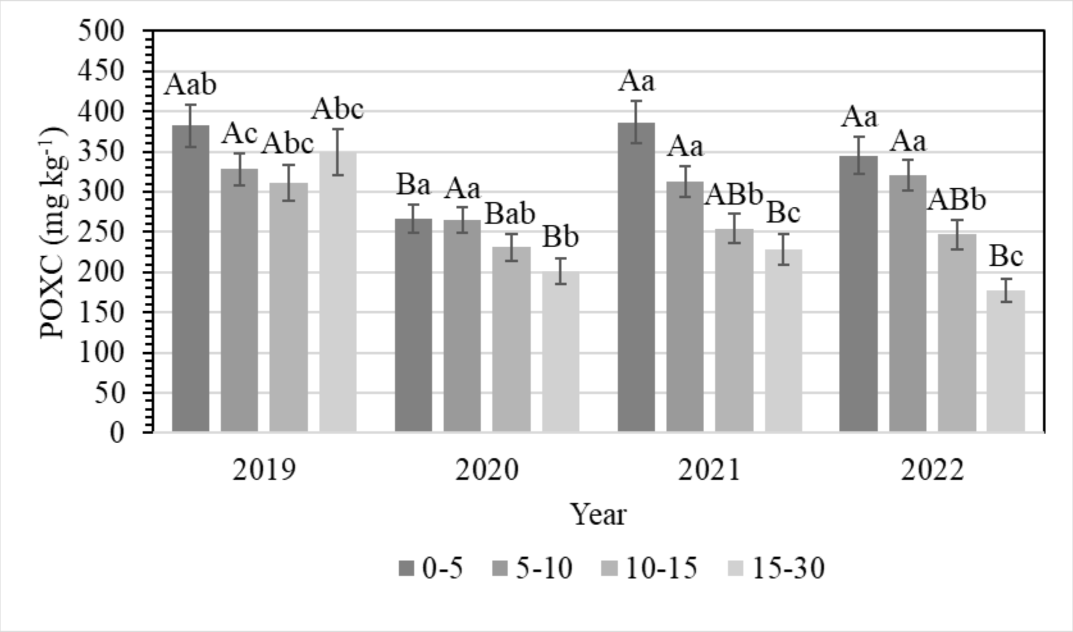

Figure 2-4. Values for permanganate oxidizable carbon (POXC) means by year and depth. Values followed by the same lowercase letters are not significantly different from other values for depth within that year and values followed by the same uppercase letters are not significantly different from other values for year within a depth at α=0.05 using Tukey's HSD.

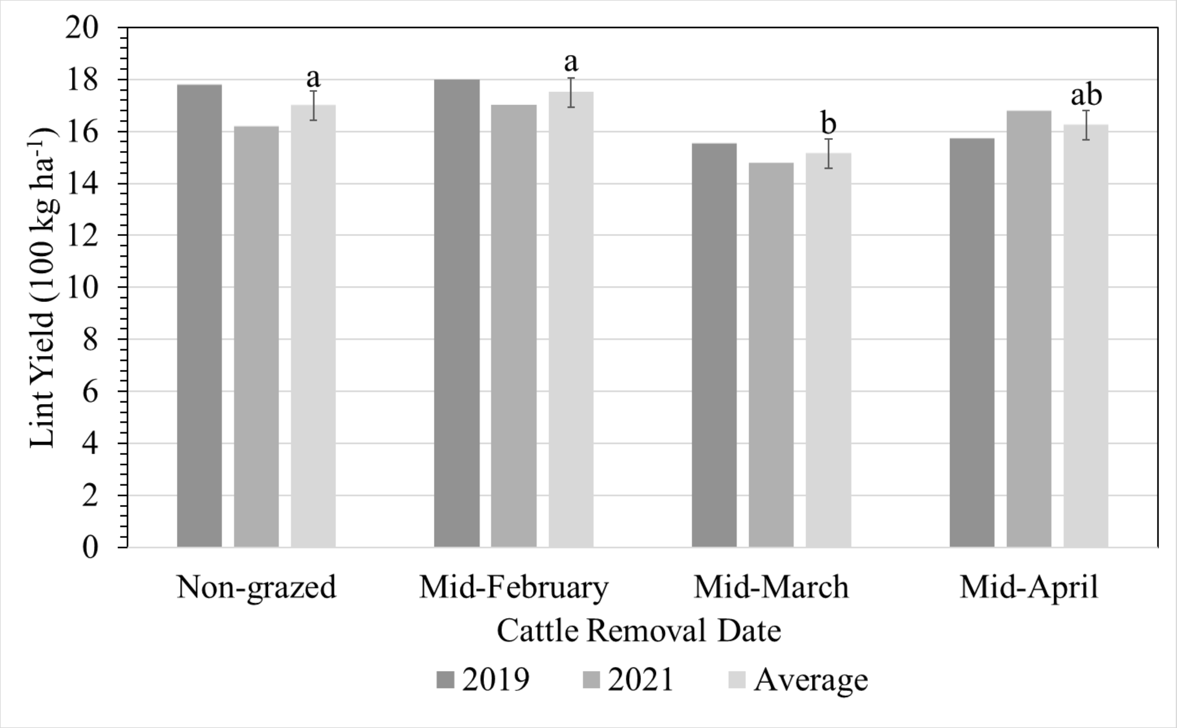

Figure 2-5. Cotton yields for 2019, 2021, and the combined values for both. Bars with the same letter are significantly different from each other at α = 0.05.

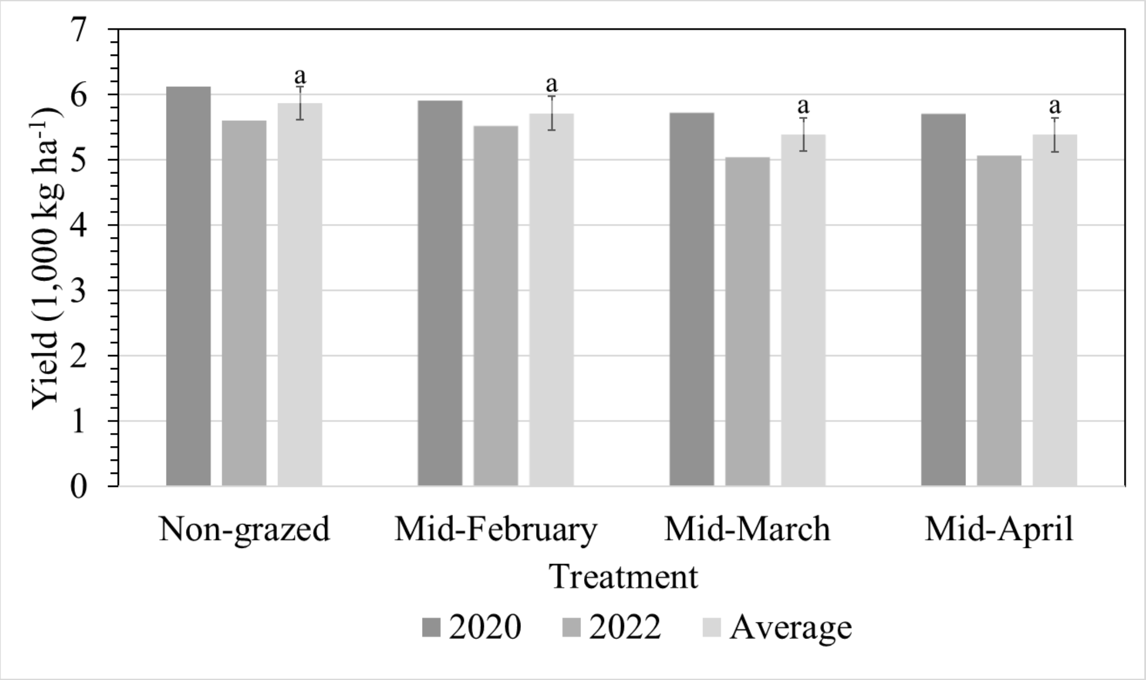

Figure 2-6. Peanut yields for 2020, 2022, and the combined average of the two years. No significant differences were observed at $\alpha = 0.05$.

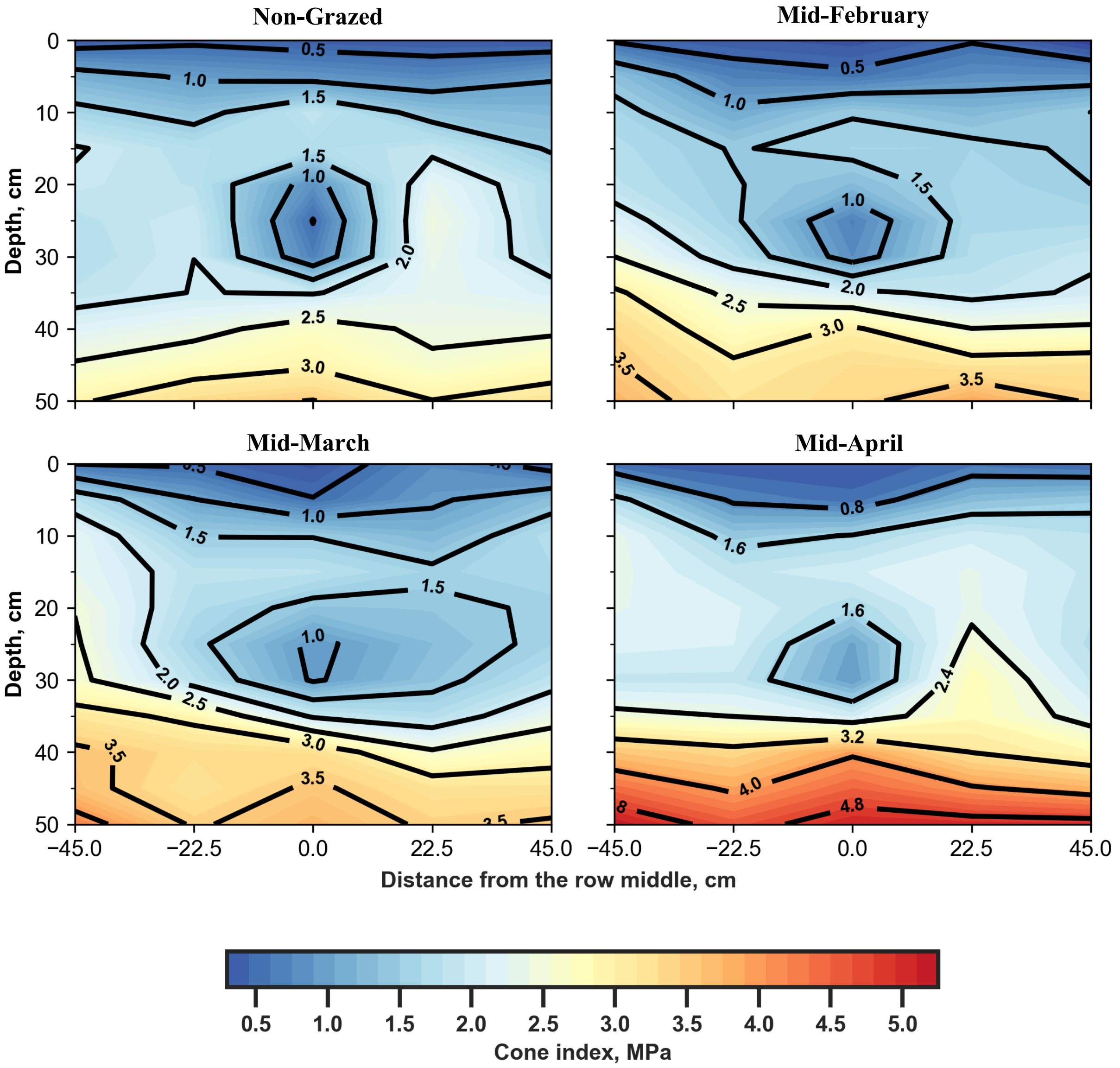

Figure 2-7. Contour maps display penetration resistance in MPa for the 0-50 cm sampling depth for each treatment for the 2022 readings.

Figure 2-8. Pictures taken on July 5, 2022, 88 days after cover crop termination showing the amount of residue left on the soil surface. The left photo is of an non-grazed control treatment, and the right photo is of a mid-April cattle removal treatment.

Chapter 3: Cover Crop Management and Preemergence Herbicides on Early Season Weed Suppression in Full Season Soybeans

Introduction

Weed management is an important aspect of row-crop production. With much of the national agricultural community moving towards conservation tillage methods to decrease soil erosion and increase soil health, weed ecology has evolved with this trend as well. Conservation tillage has led to small-seeded grasses and annual weeds, such as common lambsquarters (*Chenopodium album*), horseweed (*Conyza canadensis*), Palmer amaranth (*Amaranthus palmeri*), foxtails (*Seteria* spp.), and annual ryegrass (*Lolium multiflorum*), to become dominate weeds in cropping systems because seeds remain near the soil surface (Koskinen & McWhorter, 1986; Buhler, 1995). The increase in conservation tillage has also led to an increased reliance on herbicides to control weeds in cropping systems (Locke et al., 2006). Weeds have also adapted to the use of herbicides by evolving resistance to some herbicide modes of action. Currently 268 species across the world have developed resistance to 21 of the 31 known modes of action (Heap, 2023). Considering this evolution of herbicide resistance in weed species, integrated pest management (IPM) practices are needed.

Integrated pest management is a multifaceted approach that uses a combination of control methods to reduce the negative impact of troublesome species in production agriculture. The most common control practices include mechanical, chemical, and cultural control methods. Cultural control practices may arguably be one of the more beneficial practices because they incorporate practices into a cropping system that may provide other benefits aside from weed control, such as building soil health and protecting the environment (Teasdale et al., 1996). Crop rotations, mulching, and cover cropping are all cultural control methods that growers can incorporate into production systems (Upapdhyaya & Blackshaw., 2007). Cover crop use is already a common occurrence in the southeastern United States due to their potential to decrease soil erosion, increase soil health, and preserve soil moisture during the growing season (Chu, 2017). Cover crops also have potential to suppress early season weed growth in crops through physical and chemical means. Poaceae and Brassicaceae cover crops, such as cereal rye, barley, and radishes can inhibit weed germination with allelopathic chemicals (Creamer et al., 1996). These crops can emit allelopathic chemicals such as benzoxazinones and glucosinolates into the rhizosphere and can leach out of roots throughout the growing season and the residue for a short period of time after termination (Strum et al., 2018). Weed suppression from some of these chemicals has been observed to be 25% or higher in some cases for 2 weeks after cover crop termination (Strum et al., 2018).

A fundamental component of weed suppression with cover crops is the production of aboveground biomass. Cover crop biomass provides a physical surface barrier that can prevent weed seeds from germinating by blocking solar radiation and keeping the soil wetter and cooler for a longer period of time in the spring (Liebman & Mohler, 2001). Price et al., (2018) found that using conservation tillage in conjunction with a cover crop provides up to 3 weeks of acceptable weed control before yield losses occur. Other studies have found that using cover crops can promote early season weed suppression (Hodgskiss et al., 2022; Pittman et al., 2020; Walters et al., 2008; Florence & McGuire, 2020), and that higher amounts of biomass may accentuate these effects on the cropping system (Lemessa & Wakjira, 2015). Numerous management practices including seeding rate, planting date, termination timing, and fertilization rate affect amounts of cover crop biomass produced (Ruis et al., 2019, Mirsky et al., 2011), but adjusting planting and termination timing may be the most influential factors (Balkcom et al., 2013; Bauer & Reeves, 1999). While some studies have shown that seeding rates affect cover crop biomass production in some monocultures and mixtures (Ruis et al., 2019; Mirsky et al., 2017), other research determined that seeding rate has little effect on biomass production, especially for grass monocultures (Balkcom et al., 2023; Koehler-Cole & Elmore, 2020). Fertilizing cover crops with nitrogen improves biomass production for grass monocultures (Balkcom et al., 2023; Reiter et al., 2008), but it has mixed effects on biomass production for mixtures that contain legume species (Rouge et al., 2022).

Preemergence herbicides are another way to diversify herbicide programs to help slow down herbicide resistance. As the name implies, preemergence herbicides target weeds prior to their emergence and are considered a preventative tactic. This type of chemical application targets weeds at their most vulnerable stage to reduce the development of herbicide resistance (Sherwani et al., 2015). Once preemergence herbicides are soil incorporated and activated by rainfall or irrigation, many grass and broadleaf weeds may be suppressed for at least 30 days (Albrecht et al., 2021; Gazola et al., 2021). By pairing these preemergence herbicides with cover crops, farmers may be able to increase early season weed suppression and possibly reduce the need for postemergence applications. A study in Indiana found that monocultures and mixtures containing cereal rye in addition to a preemergence herbicide were effective at controlling waterhemp and horseweed emergence by 80% (Hodgskiss et al., 2020). Pairing preemergence herbicides with cover crops provides increased early season weed suppression (Walters et al., 2008; Reddy et al., 2003; Perkins et al., 2020). While cover crops and herbicides can help prevent weed emergence, Whalen et al., (2019) found that large amounts of cover crop biomass intercepted some of the preemergence herbicide sulfentrazone. While cover crops and preemergence herbicides both aid in weed suppression, it is unknown how different combinations of the two factors affect weed suppression. The objectives of this study were to 1) examine how different seeding rates and fertilization rates affected production of cover crop biomass and 2) evaluate how different combinations of cover crop biomass and preemergence herbicides affect early season weed suppression.

Materials and Methods

Location and Management

This experiment was conducted at two different locations. In 2022, the study was conducted at the Tennessee Valley Research and Extension Center (TVREC) in Belle Mina, AL (34.686614, -86.891272). The soil at this location was a Decatur silty clay loam (fine, kaolinitic, thermic Rhodic Paleudults). Previous management of this location was conventional tillage corn production. In 2023, the experiment was conducted at two locations. One was conducted at the Tennessee Valley Research and Extension Center (34.687253, -86.890510) and the other at the E.V. Smith Research Center (EVSRC) in Shorter, AL (32.429154, -85.890297). The soil at TVREC was a Dewey silt loam (fine, kaolinitic Typic Paleudults) and the soil at EVSRC was a Compass loamy sand (coarse-loamy, siliceous, subactive, thermic, Plinthic Paleudults). In 2023, the TVREC site followed a predominately fallow site, with the fourth rep following conventional tillage soybean production. The EVS site was managed in strip-tilled corn during the previous season. The trial was managed in a cover crop-soybean system. Plot size at TVREC was 3.05 m^{-1} wide by 9.14 m^{-1} long and was 3.66 m^{-1} wide by 9.14 m^{-1} long at EVSRC. Cover crops were planted in the fall after the harvest of previous cash crop into a conventionally tilled seedbed on a 19.05 cm row spacing with a 1205NT Great Plains grain drill (Great Plains Manufacturing Co., Salinas, KS) at EVSRC and a EWNT10-1408 Great Plains grain drill (Great Plains Manufacturing Co., Salinas, KS) at TVREC. The cover crop was a mixture of cereal rye (*Secale cereale*) and crimson clover (*Trifolium incarnatum*). Cover crops were chemically terminated at each location approximately 4 weeks before planting soybeans. Cover crops at TVREC were terminated with glyphosate at 1.35 kg ae ha^{-1}, dicamba at 0.56 kg ae ha^{-1}, and saflufenacil at 0.02 kg ai ha^{-1}. Cover crops at EVSRC were terminated with glufosinate at 0.49 kg ai ha^{-1}, and paraquat at 0.86 kg ai ha^{-1} and another application of glyphosate at 1.64 kg ae ha^{-1} and glufosinate at 0.49 kg ai ha^{-1} at planting. Cover crops were rolled with a crimper roller before planting soybeans. Soybeans were planted with a 4-row planter at a population of 7.5 seeds ft^{-1} at TVREC. After weed ratings were completed, each location was treated differently due to circumstances at each location. Soybeans at TVREC in 2022 were sprayed with glyphosate at 1.35 kg ae ha^{-1} and in 2023 no postemergence herbicide application was made. Soybeans at EVSRC were sprayed with glyphosate at 1.35 kg ae ha^{-1}, bentazon at 0.56 kg ai ha^{-1}, and acifluorfen at 0.28 kg ai ha^{-1} after weed ratings were done. Soybeans were planted on 76.2 cm row spacings at TVREC and 91.4 cm row spacings at EVSRC. A soil sample was taken from the plot area before planting the soybeans. Fertilizer and lime applications were made based on recommendations from the Auburn University soil testing lab. All fungicide and insecticide applications were made as needed based on recommendations from Alabama Cooperative Extension guidelines (Graham et al., 2023). Field work and sampling dates for each location are in tables 3-1 & 3-2.

Experimental Design

The experimental design was a 2x2x3 factorial. Treatments included cover crop seeding rate, fertilization rate, and preemergence herbicide application. The cover crop mixture seeding rates were 67.3 kg ha^{-1} of cereal rye with 17.9 kg ha^{-1} of crimson clover and 33.6 kg ha^{-1} of cereal rye with 9.0 kg ha^{-1} of crimson clover. Two fertilizer treatments of 67.3 and 33.6 kg ha^{-1} of nitrogen was applied as a 34-0-0 ammonium nitrate/ urea blend to the cover crop when rye was at the two-leaf stage, which was approximately two weeks after planting. Three preemergence herbicide treatments were made immediately following soybean planting. Treatments were applied to the plots immediately after soybean planting, using a CO_2 pressurized sprayer and four-nozzle handheld boom with AIXR 11002 tips at 140 L/ha. Treatments were *S*-metolachlor (Dual Magnum) at 1.78 and 1.42 kg ai ha^{-1} at TVREC and EVSRC, acetochlor (Warrant) at 1.26 kg ai ha^{-1} at both locations, and a nontreated check at both locations. *S*-metolachlor was applied at different rates for the two locations to represent the highest labelled rate allowed for the soil texture class.

Sampling

Cover crop biomass was sampled immediately prior to termination, which was approximately 4 weeks prior to planting the soybeans. Three, 0.25 m^2 quadrats were taken from each of the plots and dried at 100° C for at least 48 hours. Samples were then weighted to obtain dry weights for aboveground cover crop biomass. Weed counts were collected approximately 14, 28, 42, and 56 days after soybean planting (DAP). Weed counts were taken from 2, 1 m^2 quadrats from each plot at each sampling date. The number of each weed species present was recorded. Soybean yield was collected at the end of the growing season.

Data Analysis

Data was analyzed using the PROC GLIMMIX (generalized linear mixed model) and PROC REG procedures in SAS version 9.4 (SAS Institute, Cary, NC). Weed counts were subjected to Analysis of Variance (ANOVA) to evaluate the effect of herbicides over time with a repetitive measure with Poisson distribution using log link function in the model statement. Herbicides and time (days after planting) were considered fixed effects, and replication was considered random effects. No significant interaction of site year was found; hence, data was pooled over site year for weed counts. Correlations for the fixed effects and residuals were modeled using an autoregressive covariance structure by including TYPE = AR (1) in the RANDOM statement. Means were separated using the Tukey HSD test at $\alpha = 0.05$. Data was converted back from the log function to its count data representation after analysis was performed to make data easier to display. Error bars for the graphs were also converted back to count data representation and display the standard error.

Cover crop biomass was subjected to ANOVA to evaluate the effect of seeding and fertilization rates as fixed effects, and site year and rep were treated as random effects. However, no significant effect of seeding and fertilization rate on cover crop biomass was found. Later, cover crop biomass was treated as a continuous variable, and a linear regression model was fitted, with cover crop biomass as the independent variable and weed counts as the dependent variable.

Soybean data was analyzed separately for each site year because each one was treated differently after the final rating data. Herbicide was treated as a fixed effect and rep and site year were all treated as random effects. Since no differences in cover crop biomass occurred, soybean yield was not analyzed by cover crop biomass. Means were separated by using the Tukey HSD test at $\alpha = 0.05$.

Results and Discussion

Cover Crop Biomass

Seeding rate, fertilization rate, and their interaction had no effects on cover crop biomass within any site year so data was pooled across site years for analysis. Cover crop biomass was not influenced by seeding rate (P=0.6893), fertilization rate (P=0.1514), or the interaction between seeding rate and fertilization rate (P=0.4273). Cover crop biomass production ranged from 3,602 kg ha^{-1} to 9,500 kg ha^{-1} across all plots for three site years. Despite the range in cover crop biomass, the lack of statistical difference for treatments (Fig. 3-1) suggests biomass was affected by other factors and that it has the ability to compensate for differences in seeding and fertilization rates. For example, Ruis et al., (2019) determined cover crop biomass production can be influenced by other factors including planting date, termination date, and environmental conditions such as rainfall, temperature, and available soil nutrients.

Seeding rate as a sole factor had no effect on cover crop biomass production. Some cover crops, such as cereal rye can tiller more in sparse stands to increase biomass production (Haramoto, 2019; Reed & Karston, 2022). Others have found planting cereal rye in a mixture with a legume can produce similar levels of biomass to a rye monoculture (Murrell et al., 2017; Chintala et al., 2022). Cereal rye can dominate a mixture even at lower seeding rates. Poffenberger et al., (2015) found that a cereal rye/ legume mixture was able to produce similar biomass levels even when rye was reduced to 25% of the mixture composition. Since cereal rye has such a large ability to produce biomass at lower seeding rates, it is likely the reason why high and low seeding rates of this mixture did not influence cover crop biomass.

Two factors could have potentially led to a lack of treatment differences for fertilizer application. The first was the species in the cover crop mixture. While cereal rye requires soil available nitrogen for proper growth, crimson clover is a legume and fixes its own nitrogen. Mixtures of grasses and legumes can be very productive at producing biomass in many cases, even without supplemental nitrogen (Tracy et al., 2018; Yu et al., 2016). The inclusion of legumes may have helped more nitrogen to be free for cereal rye to uptake from the soil (Fujita et al., 1992). Previous site management may have led to different soil nitrogen contents since the site years were previously managed under corn, soybean, and fallow. Soybeans are also a legume, so as those residues degrade nitrogen is released to the mineral form that is available to other crops (Green & Blackmer, 1995). Mineral nitrogen in the soil may have been immobilized in the soil behind corn production as microbes use more nitrogen to break down residues (Shipley et al., 1992). Excess mineral nitrogen may have also been left in the soil from the previous corn crop because the area was under a drought for much of the summer and lead to lower corn yields. Soil in the fallow plot may have contained some soluble N that the cover crop could use due to the finer soil texture, or the soil nitrogen was depleted and contributed little to cover crop growth. Studies such as Balkcom et al. (2023) have found that rye fertilization can increase biomass production in a rye monoculture but did not examine its effects on biomass production in mixtures. Other studies have found nitrogen fertilization did not significantly increase cover crop biomass production in mixtures, and that environmental differences can cause variability in cover crop biomass production (Vann et al., 2018).

Weed Counts

Weed counts were affected by cover crop biomass (P=<0.0001), herbicide (P=<0.0001), DAP (P=<0.0001), and the interaction between herbicide and DAP (P=<0.0001). Weed populations differed between site years. Major occurring weed species were present in large amounts across the test and minor occurring weed species were found sparsely across the test. At

TVREC 2022, weed populations were 48% broadleaves and 52% grasses. At TVREC 2023, weed populations were 35% broadleaves and 65% grasses. The major occurring weed species present during both site years in decreasing order of frequency were large crabgrass (*Digitaria sanguinalis*), barnyardgrass (*Echinochloa crus-galli*), Palmer amaranth (*Amaranthus palmeri*), prickly sida (*Sida spinosa*), and morningglories (*Ipomoea* spp.). Other weed species not consistently represented were goosegrass (*Eleusine indica*), velvetleaf (*Abutilon theophrasti*), spurred anoda (*Anoda cristata*), and carpetweed (*Mollugo verticillata*). At EVSRC 2023, weed populations consisted of 13% broadleaves, 23% grasses, and 64% sedges. Major occurring weed species in descending order were yellow nutsedge (*Cyperus esculentus*), large crabgrass (*Digitaria sanguinalis*), broadleaf signalgrass (*Urochloa platyphylla*), morningglories (*Ipomoea* spp.), Palmer amaranth (*Amaranthus palmeri*), and smallflower morningglory (*Tamnifolia japonica*). Other weeds not consistently represented were Canada goldenrod (*Solidago canadensis*), goosegrass (*Eleusine indica*), barnyardgrass (*Echinochloa crus-galli*), and carpetweed (*Mollugo verticillata*).

Cover crop biomass had a significant, positive effect (P=0.0001) on weed suppression (Fig. 3-2). As biomass increased, a decrease in weed counts was observed. While the regression was significant, the R-squared value is low (R^2=0.1327), showing that cover crop biomass only explains a small amount of the early season weed suppression. Weed density likely also affects the ability of cover crops to suppress weeds. The TVREC 2022 site year had the lowest weed densities and at the two-week weed rating no weeds were present. The other two site years had higher weed densities and weeds were present at the two-week rating date. This is similar to findings of other studies examining effects of cover crop biomass on weed growth. Price et al.

(2018) found that using cover crops in conservation tillage systems could provide 3 weeks of weed control. Levels of biomass greater than 8,000 kg ha^{-1} have been shown to decrease weed emergence by 75% (Mirsky et al., 2013). Other studies have found that higher levels of biomass can suppress weeds for longer periods of time (Pittman et al., 2020; Florence & McGuire, 2020; Lemessa & Wakjira, 2015).

Preemergence herbicides had a significant effect on weed counts (P=0.0001) and the data is displayed in figure 3-3. Both *S*-metolachlor and acetochlor controlled weeds significantly better than the non-treated plots. *S*-metolachlor controlled weed significantly better than acetochlor, but the difference between the two was small numerically. While cover crops may be helpful in controlling weeds, they were unsuccessful at providing season-long weed suppression when used alone. This shows that including a preemergence herbicide with cover crop residues can increase early season weed control. Some studies have tried to examine whether cover crop residues intercept preemergence herbicide and prevent it from reaching the soil (Whalen et al., 2019). While soil concentrations were not examined in this study, both preemergent herbicides were successfully activated and provided weed control in all levels of cover crop biomass according to the data. Other studies have looked at various other preemergence herbicides and the chloroacetamides (Walters et al., 2008; Perkins et al., 2020; Reddy et al., 2003) and found that they were successful in controlling weeds better than the nontreated in cover crop residues. Other studies have found increased control of herbicide resistant weeds, such as Palmer Amaranth, with acetochlor compared to some other preemergence herbicides (Cahoon et al., 2015; Perkins et al, 2020). Emerged weeds were also significantly affected by sampling date or DAP (Fig. 3-4). As expected, weed counts increased over time. Differences were observed between 14 and 28 DAP and also between 28 and 56 DAP. Weed counts increased significantly at the 56 DAP rating date over the 14 and 28 DAP rating dates.

Preemergence herbicide by days after planting interaction was also significant (P=0.0001) and is displayed in figure 3-5. The 14-, 28-, and 42-day rating dates that received a preemergence herbicide had significantly less weeds than all rating dates for the nontreated plots. The 54-day rating for both herbicide treatments were statistically similar to the 14- and 28-day nontreated plot. This result shows that preemergence herbicide suppressed weed emergence for approximately 42 days. This is similar to other studies that have found the long chain fatty acid inhibitor herbicides have good control of both grasses and broadleaves for 5 to 6 weeks after application (Riberio et al., 2021; Parker et al., 2005, Priess et al., 2020). The use of preemergence herbicide reduced the need for an early postemergence herbicide treatment compared to the nontreated plots. While a cover crop can aid in weed suppression, these results that a preemergence herbicide application can increase weed suppression for longer into the season. This provides more flexibility for timing of a postemergence herbicide application or could reduce the number of postemergence applications needed.

Soybean Yields

Soybean yields were affected by preemergence herbicide in two out of the three site years. TVREC 2022 was not affected by preemergence herbicide treatment (P=0.1142) while TVREC 2023 (P=0.0002) and EVREC 2023 (P=0.0506) were affected (Table 3-3). The growing season at TVREC 2022 was under extreme drought conditions and explains the low soybean yields across all treatments and the lack of differences. Yields were lower than the non-treated check for both preemergence herbicides at TVREC 2023 and *S*-metolachlor was higher than the non-treated check at EVSRC in 2023. Using the herbicides provided control early in the season which was able to give the soybeans time to grow without weed competition. While the weeds were not controlled at TVREC 2023 throughout the season, the herbicide treatment still helped them to yield higher. Other studies have found that using a preemergence herbicide can be effective at increasing crop yields when certain weeds, such as Palmer amaranth are present (Oliveira et al., 2017; Perkins et al., 2020).

Conclusion

Cover crops can suppress early season weed emergence in soybeans. A major component contributing to weed suppression with cover crops is production of high biomass that will persist on the soil surface. Cover crop biomass production in mixtures can be influenced by many factors, but some may be more important than others. Seeding rates and fertilization rates of cover crops should be decided based on local recommendations for cover crops, as this study showed minimal differences in biomass production from different rates of either. Earlier planting dates in the fall is the best way to ensure higher cover crop biomass production based on other research in the Southeast. While cover crops have potential to limit weed emergence, combining it with a preemergence herbicide at soybean planting provides much longer weed suppression into the season. Using a preemergence herbicide in conjunction with a cover crop can reduce weeds that need to be controlled with a postemergence herbicide application or eliminate the need for a second postemergence herbicide application to control troublesome weeds. Buildup of herbicide resistance may be reduced by decreasing the reliance on postemergence herbicides and diversifying weed control programs with these practices.

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Tables and Figures

Table 3-1. Dates for field operations and samplings for each year at the Tennessee Valley Research and Extension Center

Operation	2021	2022	2023
Cover Crop Biomass Sampling	-	Apr. 8	Apr. 12
Cover Crop Termination	-	Apr. 15	Apr. 13
Soybean Planting Date	-	May 10	May 11
Preemergence Herbicide Application	-	May 11	May 12
14 DAP Weed Rating	-	-	May 31
28 DAP Weed Rating	-	June 14	June 15
42 DAP Weed Rating	-	June 28	June 30
56 DAP Weed Rating	-	July 12	July 12
Postemergence Herbicide Application		Aug. 3	-
Soybean Harvest	-	Oct. 24	Oct. 16
Cover Crop Planting	Oct. 22	Oct. 20	-
Cover Crop Fertilization	Nov. 8	Nov. 4	-

Table 3-2. Dates for field operations and sampling dates for each year of the study at the E.V. Smith Research Center.

Operation	2022	2023
Cover Crop Biomass Sampling	-	Apr. 19
Cover Crop Termination	-	Apr. 29
Soybean Planting Date	-	June 1
Preemergence Herbicide Application	-	June 2
14 DAP Weed Rating	-	June 16
28 DAP Weed Rating	-	July 3
42 DAP Weed Rating	-	July 14
56 DAP Weed Rating	-	July 28
Postemergence Herbicide Application	-	Aug. 29
Soybean Harvest	-	Oct. 23
Cover Crop Planting	Nov. 3	-
Cover Crop Fertilization	Nov. 17	-

Table 3-3. Soybean yields for all three locations averaged across herbicide treatment. Values with the same letter within a location are not statistically different from each other at α=0.05.

Treatment	Soybean Yield		
	TVREC 2022	TVREC 2023	EVSRC 2023
	——— (kg ha^{-1}) ———		
S-metolachlor	1526 a	4142 a	3860 a
Acetochlor	1472 a	3927 a	3537 ab
Non-treated	1291 a	3322 b	3046 b
SE	82.79	130.8	227.3

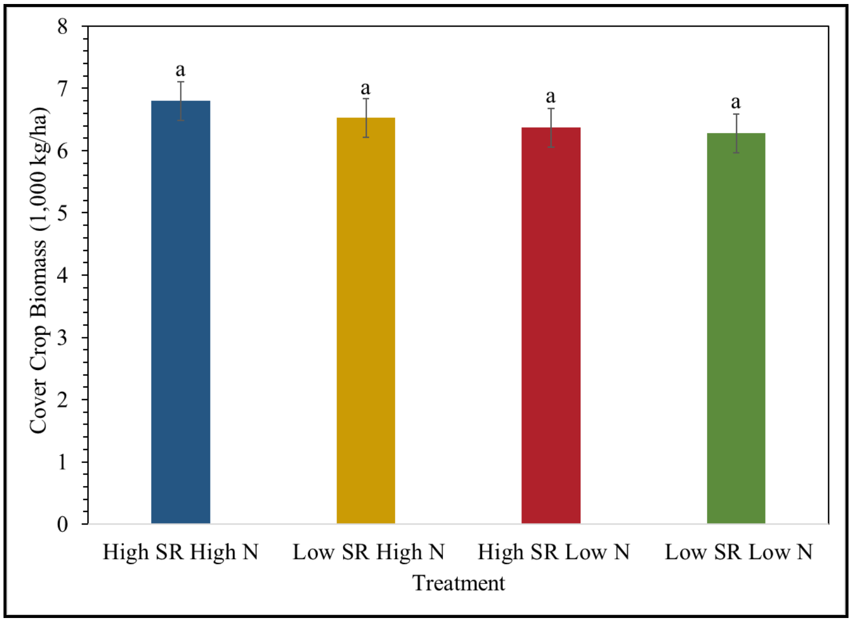

Figure 3-1. Cover crop biomass averaged across all site years by seeding rate (SR) and fertilization rate (N). Treatments with different letters are significantly different from each other at α=0.05 using Tukey's HSD.

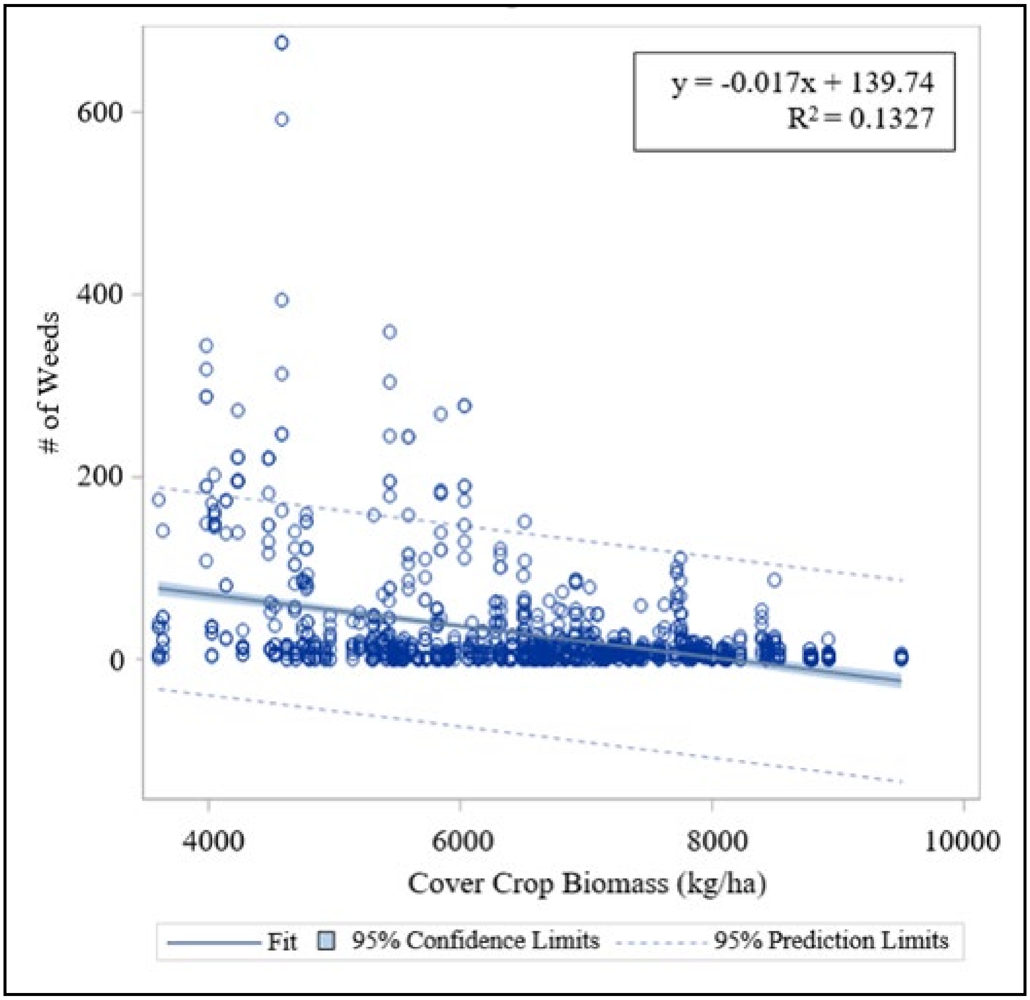

Figure 9. Linear regression combining all three site years comparing weed counts at every rating date to cover crop biomass production from each plot. The regression is significant at α=0.05.

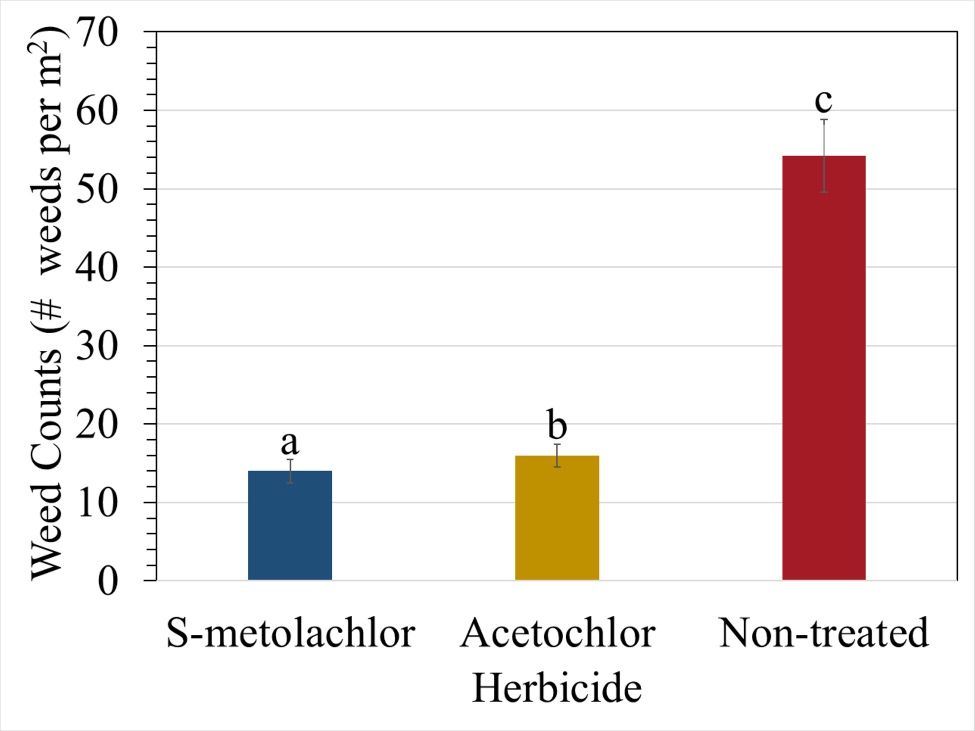

Figure 10. Effect of herbicide treatment on weed counts, averaged across all site years. Treatments with different letters are significantly different from each other at α=0.05 using Tukey's HSD.

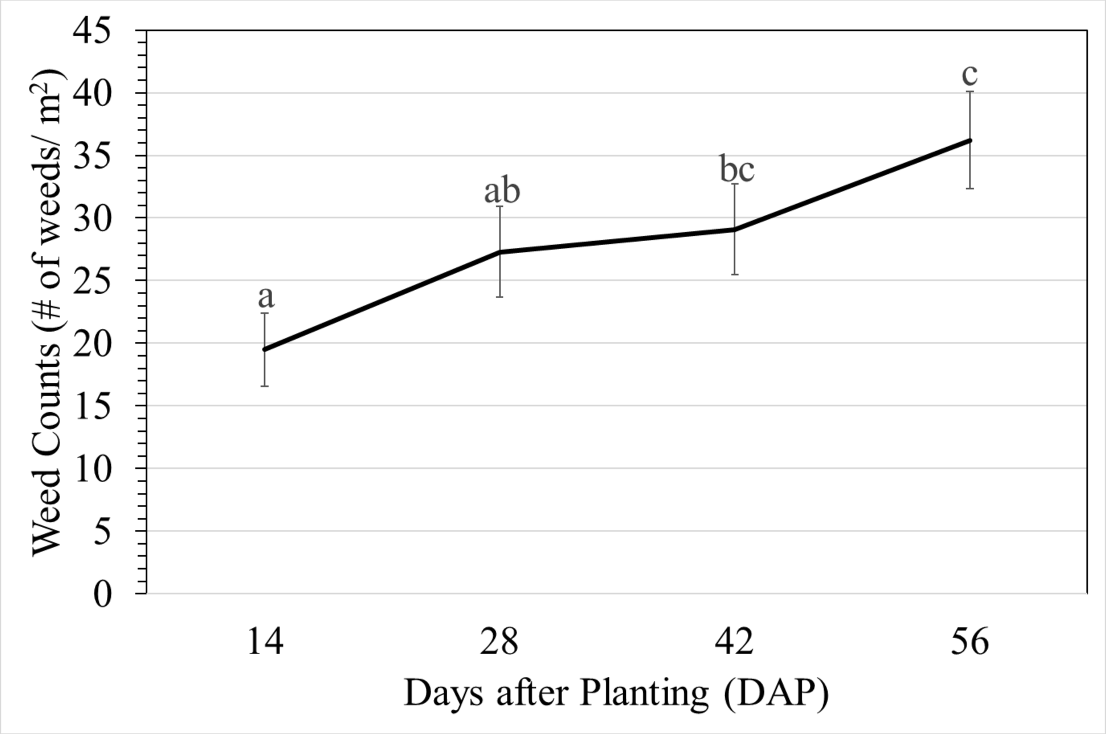

Figure 3.4. Cumulative weed counts averaged across all site years by sampling time (DAP). Treatments with different letters are significantly different from each other at α=0.05 using Tukey's HSD.

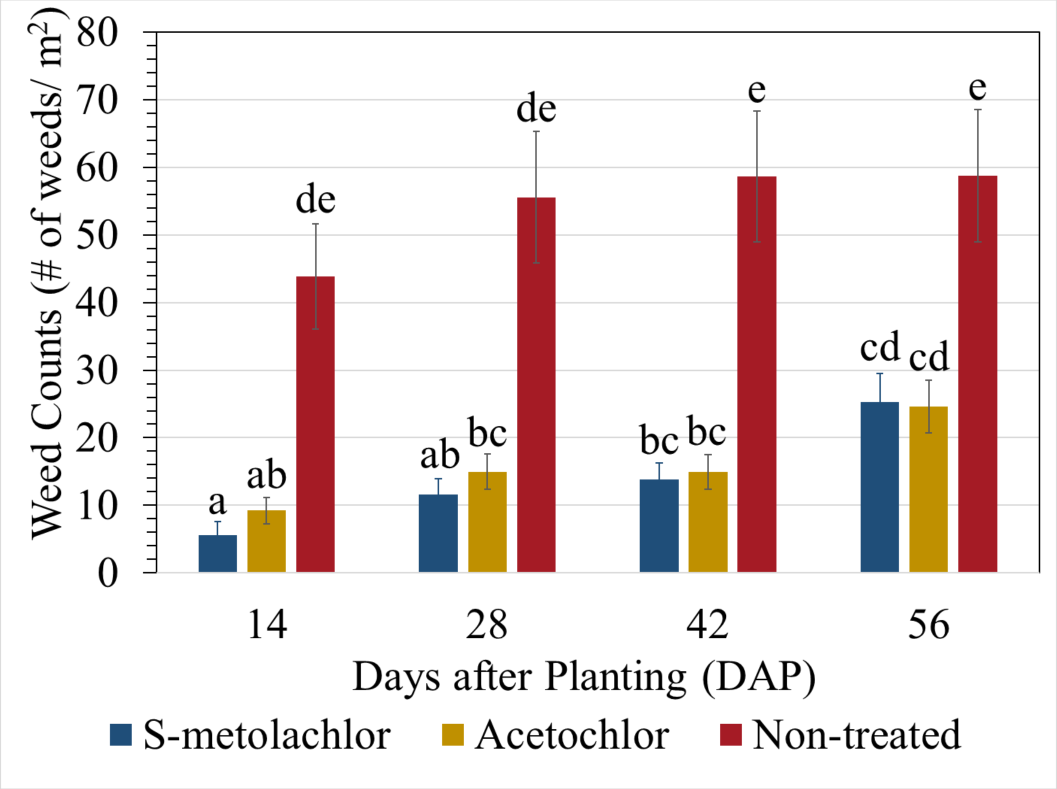

Figure 3.5. Cumulative weed counts averaged across all site years by the interaction between herbicide treatment and sampling date. Treatments with different letters are significantly different from each other at α=0.05 using Tukey's HSD.