INTEGRATING SUSTAINABLE MANAGEMENT PRACTICES TO IMPROVE SOIL HEALTH AND ROW CROP PRODUCTIVITY

by

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(Under the Direction of Henry Yabbey Sintim)

ABSTRACT

Degraded soil health conditions are major constraints to the sustainable production of row crops in the state of Georgia and most states in the Southeastern United States. The warm temperatures, as well as intensive rainfall, rapid mineralization of organic matter, and depletion of mineral-derived plant nutrients. Moreover, reliance on conventional tillage (CT) for seedbed preparation further degrades soil health. Management practices such as conservation tillage, cover crops (CCs), and organic amendments (OAs) are employed to improve soil health and row crop productivity. However, there are shortcomings associated with individual management practice. Integrating these practices could mitigate the limitations and augment the benefits of each management practice. Field studies were established to evaluate the individual and integrated impacts of tillage, CCs, and OAs on soil health and row crop productivity. The row crops evaluated were corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and peanut (Arachis hypogaea L.). Cereal rye (*Secale cereale;* CR) was used as the cover crop, and the OAs was a combination of animal manure and biochar (BC). The studies were established at two locations: (1) the USDA-ARS Bellflower Farm in Tifton and (2) the Southeast Georgia Research and Education Center in Midville, GA.

In the first study, the integration of CCs and OAs into strip tillage (ST+Int) minimized soil compaction compared to strip tillage (ST) after tillage operations in the third year. Overall, integrating CCs and OAs into CT (CT+Int) and the ST+Int increased soil respiration and organic matter within the 0-15 cm depth, but the effects were not consistent across years. The various management systems had a minimal impact on cotton productivity and fiber quality. Moreover, the integrated sustainable management systems did not consistently improve soil biochemical properties. The findings of the second study showed that reduced tillage (RT) produced similar cotton, peanut, and corn yields as the CT, indicating the ST was effective in seedbed preparation. Cotton responded favorably to poultry litter (PL) application in RT and CR (RT+CR+PL), especially when compared to only RT+CR. Also, integrating RT, CR, PL, and BC did not substantially improve soil health.

INDEX WORDS: soil health, row crops, sustainable management practices, regenerative agricultural practices, conventional tillage, conservation tillage, strip tillage, reduced tillage, cover crops, cereal rye, organic amendments, poultry litter, biochar.

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DEDICATION

This dissertation is dedicated to my mum, who passed away on June 15, 2025, for consistently and fervently bearing me up in prayers to excel in all my pursuits.

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CHAPTER 1

GENERAL INTRODUCTION

1.1. Background

The warm climate of the Southeastern United States is ideal for growing peanut (*Arachis hypogaea* L.), cotton (*Gossypium hirsutum* L.), and corn (*Zea mays* L.). The Southeastern states are the largest producers of cotton and peanut in the USA (Bukowski and Ates, 2023; USDA-ERS, 2025a). The state of Georgia is the leading producer of peanut in the USA, contributing 40-55% of the peanut production (Monfort et al., 2022; Hand et al., 2023). Georgia also ranks as the second-largest cotton producer in the USA (Hand et al., 2023). According to the 2024 Ag Snapshots, peanut, cotton, and corn contributed a total of $2.6 billion to the agricultural industry of the State of Georgia (Kane, 2024). Also, these crops are vital in supplying raw materials for food, fiber, and industrial products. The seeds and by-products of peanut, corn, and cotton serve as important food sources for people and feed for livestock (Khan et al., 2020; Machado et al., 2025; USDA-ERS, 2025b).

Degraded soil health conditions are major constraints to the sustainable production of peanut, cotton, and corn in Georgia and the Southeastern USA at large. Soil health is defined as the capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans (USDA-NRCS, 2024). The climate of most of the southeastern region is humid subtropical, having hot and long summers and generally moist conditions (Konrad et al., 2013). Frequent and intense rainfall accompanied by warm temperatures leads to topsoil erosion, rapid weathering of primary minerals and mineralization of organic matter, and the depletion of mineral-derived plant nutrients (Pincus et al., 2017; Nunes et al., 2019; Amissah et al., 2024). In Georgia, Ultisols are the predominant soil order, which are highly weathered. The dominant clay mineralogy is kaolinite, a 1:1 clay which has low cation exchange capacity (less than 16 $cmol_c$ kg^{-1}) and low buffering capacity. In addition, the soils have low organic matter and are depleted of essential plant nutrients (Ankomah et al., 2024; Amissah et al., 2024; Truman et al., 2010; MacHmuller et al., 2015).

Moreover, reliance on conventional tillage for seedbed preparation can degrade soil health. Conventional tillage breaks up compacted soil layers while improving soil aeration, seed germination, and root development (Claassen et al., 2018; Shahzad et al., 2019). Intensive tillage could, however, be counterproductive by breaking soil aggregates into smaller particles, making the soil more vulnerable to erosion and increasing carbon loss (Franklin and Bergtold, 2020; Magdoff and Harold, 2021). Extensive tillage could also disrupt the composition, abundance, and activities of soil microorganisms (Agyei et al., 2024; Mathew et al., 2012; Nunes et al., 2020). Crop rotation, conservation tillage, cover crops, and organic amendments are common sustainable management practices or regenerative agricultural practices which can be implemented to improve soil health. Soil management practice can be termed as sustainable when the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing the soil functions that enable those services or biodiversity (FAO, 2015). Management practices that can restore agro-ecosystems, particularly soil are referred to as regenerative agricultural practices (Schreefel et al., 2020).

Planting peanut, cotton, and corn in rotation provides benefits such as the enhancement of biological function and diversity, as well as the potential to break pest cycles (Reddy, 2017; Venter et al., 2016). In addition, conservation tillage, cover crops, and organic amendments are important management practices that are employed to enhance soil health. Conservation tillage systems reduce soil erosion and enhance soil physical, chemical, and biological properties (Franklin and Bergtold, 2020 ; Mitchell et al., 2017; Nunes et al., 2020; Agyei et al., 2024). In Georgia, strip tillage is the most common type of conservation tillage, used on roughly 50% of the state's cotton acreage. With strip tillage, only the narrow strips (15 cm) within rows where plants will grow are tilled (Hand et al., 2023). Cover crops offer numerous soil health benefits, such as controlling erosion, cycling nutrients, and sequestering carbon (Sharma et al., 2018; Blanco-Canqui et al., 2015). Poultry litter is a rich source of both macro- and micronutrients, enriching the soil when applied as an amendment (Chastain et al., 2010; Mitchell and Tu, 2006). Additionally, incorporating carbon input like biochar can further increase soil organic carbon and enhance overall soil health (Agegnehu et al., 2015).

1.2. Significance of Study

Despite the benefits of conservation tillage, cover crops, and organic amendments, there are unique limitations associated with individual practices. For instance, conservation tillage has an advantage over conventional tillage in improving soil. However, converting from conventional tillage to conservation tillage could lead to short-term soil compaction issues, weed pressures, and stratification of mineral nutrients (Franzluebbers, 2002; Siri-Prieto et al., 2007; Wright et al., 2007; Franzluebbers and Stuedemann, 2008; Ankomah et al., 2024). Soil compaction could adversely affect crop growth and development. Soil compaction reduces the root volume available for nutrient uptake (Hamza and Anderson, 2005). For instance, cotton has poor seedling vigor, and therefore compacted soils can have an adverse impact on cotton productivity (Snider et al., 2016; Maeda et al., 2023). Also, due to the prevalence of weeds in a conservation tillage system, there may be over-reliance on herbicides for weed control. Cover crops and organic amendments are key soil health management practices that can be integrated into both conventional and conservation tillage systems to mitigate the limitations and augment the benefits of each tillage system.

Cover crop systems fulfill two of the soil health principles recommended by the (USDA-NRCS, 2024), which are maximizing soil cover and maintaining living roots. Cereal rye is a common cover crop grown in the Southeastern US and the USA at large due to its winter hardiness and high biomass production (Huddell et al., 2024). The substantial biomass generated by cereal rye helps in minimizing soil erosion, suppressing weeds, and enhancing soil carbon (Sainju et al., 2007; Silva and Bagavathiannan, 2023; Sainju et al., 2007). The allelopathic properties of cereal rye also helps in controlling some weed species. Allelopathic compounds such as phenolic acids and luteoline glucuronides have been found in cereal rye root ad shoot tissue (Silva and

Bagavathiannan, 2023). Also, cereal rye is a good scavenger of nutrients, taking up nutrients which otherwise could be lost, particularly during the winter months (Fageria et al., 2005; Endale et al., 2010). Despite its many benefits, cereal rye can have a high carbon-to-nitrogen (C/N) ratio if terminated late. A study conducted by (Otte et al., 2019) indicated that the C/N ratio of cereal rye was 35 and 48 in the first and second years, respectively, when termination was done late. A study conducted by (Preza-Fontes et al., 2022) showed that including cereal rye in a conservation tillage system decreased corn yield. This suggests microbial immobilization during cereal rye decomposition, as evidenced by reduced N uptake in corn biomass at the R6 (maturity) stage.

Including poultry litter in a cereal rye system and a conservation tillage system could help improve nutrient cycling. Poultry litter is a rich source of plant essential nutrients (Chastain et al., 2010; Ankomah et al., 2024) and could contain microorganisms that can potentially help in the mineralization of cereal rye and the release of nutrients during the active crop season (Chastain et al., 2010; Habteselassie et al., 2022; Ankomah et al., 2024). Poultry litter has been demonstrated to enrich soil nutrients (Nyakatawa et al., 2001; Mitchell and Tu, 2006; Endale et al., 2010). Other studies have reported improvement in soil health and yield benefits with the application of poultry litter (Nyakatawa et al., 2001; Lin et al., 2018; Adeli et al., 2019, 2022, 2024a). A study by Nyakatawa et al. (2001) showed that applying poultry litter in a conservation tillage and cereal rye system increased soil organic matter. Adeli et al. (2019) reported a 12% increase in cotton lint yield with poultry litter application, with a subsequent study showing a 42% increase in cotton lint yield when poultry litter was combined with biochar and inorganic fertilizer (Adeli et al., 2022).

Furthermore, Adeli et al. (2024b) observed increased corn grain yields with the application of poultry litter. Also, a review paper by Lin et al. (2018) indicated that poultry litter increased corn, cotton, and peanut yields.

Although poultry litter enriches soil nutrients, surface application in conservation tillage systems is prone to nutrient losses (Endale et al., 2010b). A stable carbon source like biochar can be applied together with poultry litter to minimize nutrient loss and build soil organic matter (Agegnehu et al., 2015; Giannetta et al., 2023; Kabir et al., 2023). Biochar is produced under limited oxygen conditions and at higher temperatures (around 600 °C), making it a stable carbon source that could persist longer in the soil when applied as an amendment. Moreover, the porous structure and large surface area make biochar effective in nutrient retention (Kabir et al., 2023; Allohverdi et al., 2021). In contrast, the high C/N ratio of biochar could result in N immobilization, potentially limiting the amount of N mineralized to meet crop demand, especially at the early growth stages (Abban-Baidoo et al., 2024). Also, the high C/N ratio of BC could disrupt the soil microbial community and activities (Bossolani et al., 2023; Ankomah et al., 2024). Combined application of poultry litter and biochar could potentially build soil organic matter while enhancing nutrient availability. Due to the limitations associated with conservation tillage, cereal rye, poultry litter, and biochar, integrating them could foster complementary benefits and improve soil health.

1.3. Objectives

The overall goal of the research is to improve soil health and row crop productivity by integrating sustainable management practices. Specific objectives were to:

1. Integrate cover crops and organic amendments into conventional and conservation tillage systems to offset their limitations on soil health and cotton productivity.
2. Assess the impact of individual and integrated sustainable management practices on soil biological and chemical properties.
3. Evaluate the impacts of regenerative agricultural practices on row crop productivity, quality, and nutrient uptake.
4. Evaluate the complementary effects of reduced tillage, cereal rye, poultry litter, and biochar on soil health in row crop production systems.

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CHAPTER 2

INTEGRATING COVER CROPS AND ORGANIC AMENDMENTS TO MITIGATE THE LIMITATIONS OF TILLAGE ON SOIL HEALTH AND COTTON PRODUCTIVITY

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Abstract

Various tillage systems have limitations on soil health, such as the degradation of soil structure and organic matter under conventional tillage (CT) systems, as well as short-term soil compaction in conservation tillage systems. A three-year field experiment was established to evaluate the integration of cover crop (CC) and organic amendments (OA) into CT and strip tillage (ST) systems, and their impact on soil properties and cotton (*Gossypium hirsutum* L.) productivity. The CC was cereal rye (*Secale cereale*), and the combined application of animal manure and biochar constituted the OA. In the third year, differences in soil compaction between the CT and ST systems were observed when the measurements were made after tillage. Moreover, integrating CC and OA under the CT and ST systems increased the soil depth to compaction zones. Soil compaction was observed at 27.5-cm depth under CT, at 30-cm depth under CT integrated with CC and OA, at 10-cm depth under ST, and at 15-cm depth under ST integrated with CC and OA, using 2 MPa as the threshold. In general, the integration of CC and OA tended to increase soil respiration, organic matter, and available nutrients, but the effects were not consistent across years and soil depth. Despite differences in the various soil health properties, the management systems had minimum impact on cotton productivity and fiber quality, indicating the strip tillage was effective in preparing the seedbed. Moreover, the differences in soil properties were not at yield-limiting levels within three years of the study.

2.1. Introduction

Conventional tillage systems have been historically implemented for seedbed preparation to enhance seed germination and plant establishment (Claassen et al., 2018; Shahzad et al., 2019b). The conventional tillage practice breaks up compacted layers and improves soil aeration and root development. However, continuous and intensive tillage operations pulverize soils, making them susceptible to erosion due to less crop residue left on the soil (Franklin and Bergtold, 2020). Moreover, continuous and intensive tillage operations facilitate soil carbon loss (Franklin and Bergtold, 2020; Shahzad et al., 2022), which is exacerbated by the climatic conditions in the Southeastern United States, where this study was conducted. Warm temperatures coupled with well-distributed rainfall conditions in the region lead to the rapid mineralization of soil organic matter (Konrad et al., 2013). There has been increased interest in conservation tillage systems to improve overall soil health (Bergtold et al., 2020; Farmaha et al., 2022).

Conservation tillage is broadly defined as any tillage practice that has less disturbance on the soil and has at least 30% of crop residue left on the soil surface (Conservation Technology Information Center, 2004). Such practices include no-tillage and various forms of reduced tillage like strip tillage, mulch tillage, and ridge tillage (Busari et al., 2015; Claassen et al., 2018) Conservation tillage has been documented to provide soil health benefits such as minimization of soil erosion, and improved soil physical, chemical, and biological properties (Franklin and Bergtold, 2020; Mitchell et al., 2017; Kingery et al., 1996). Conservation tillage has an advantage over conventional tillage in conserving soil and water (Franklin and Bergtold, 2020). However, there are short-term soil compaction issues and stratification of mineral nutrients associated with converting from a conventional tillage system to a conservation tillage system (Franzluebbers, 2002; Siri-Prieto et al., 2007; Wright et al., 2007; Franzluebbers and Stuedemann, 2008). Cotton has poor seedling vigor and therefore compacted soils can have an adverse impact on cotton productivity (Snider et al., 2016; Maeda et al., 2023). Also, due to the prevalence of weeds in a conservation tillage system, there may be over-reliance on herbicides for weed control.

Cover crops and organic amendments are key soil health management practices that can be integrated into conventional and conservation tillage systems to offset the limitations and augment the benefits of both tillage systems. Cover crops and organic amendments have been shown to improve soil health in the Southeastern USA (Nyakatawa et al., 2001; Adeli et al., 2019, 2024). Cover crops provide several ecosystem benefits which include erosion control, nutrient cycling, and carbon sequestration (Sharma et al., 2018; Blanco-Canqui et al., 2015). Cereal rye (*Secale cereale* L.) for instance, produces high biomass which enriches the soil with carbon and can suppress weeds when included in a conservation tillage system (Johnson et al., 2001; Sainju et al., 2007; Hand et al., 2019). In addition, cereal rye is notably known to scavenge for nutrients thereby preventing them from being leached out of the active root zone of crops (Fageria et al., 2005; Endale et al., 2010).

Animal manure is replete with both macro- and micro-nutrients which enriches the soil when used as a soil amendment (Chastain et al., 2010). Several studies reported increased cotton (*Gossypium hirsutum* L.) lint yield with the application of various forms of animal manure (Endale et al., 2010; Nyakatawa et al., 2000; Reddy et al., 2004, 2007). In Georgia, poultry litter and cattle manure are two important sources of animal manure for land application. According to the Georgia 2023 Ag Snapshot, broiler and beef production contributed $4.2 billion and $659 million to the agricultural economy of the state, representing the first and fifth most valuable agricultural commodity, respectively (Kane, 2023). Application of poultry litter in a no-tillage cropping system was found to improve various soil biochemical properties, including microbial biomass C, total C, soil pH, total N, and available P (Adeli et al., 2007). Also, the long-term application of cattle manure improved several soil health properties, as well as the yield stability of corn (*Zea mays*) (Maharjan et al., 2021; Das et al., 2023).

Despite the soil health and agronomic benefits, there are environmental concerns with the application of animal manure, especially in conservation tillage systems. Runoff of nutrients, particularly phosphorus into water bodies is common with the surface application of animal manure in conservation tillage systems (Endale et al., 2010). A stable carbon source like biochar can be applied together with animal manure to minimize environmental impacts (Adeli et al., 2022). Biochar is produced via pyrolysis, which is combustion (at about 300-700 °C) under limited oxygen conditions. The process makes biochar a stable carbon source and an important soil amendment in building soil organic carbon. In addition, biochar has a large surface area and enhances soil nutrient retention (Jeffery et al., 2011; Shahzad et al., 2018; Allohverdi et al., 2021).

As conventional and conservation tillage systems have various limitations, the objective of the study was to evaluate the integration of cover crops and organic amendments into both tillage systems to offset their limitations on various soil properties and cotton productivity. We expected the integration of cover crops and organic amendments to minimize soil compaction issues common with transitioning into conservation tillage systems, as well as the degradation of soil organic matter associated with conventional tillage systems.

2.2. Materials and Methods

2.2.1. Experimental Site

Field experiments were established in spring 2020 through to spring 2023 at the USDA-ARS Bellflower Farm in Tifton, GA (31°30'32.83" N, 83°33'29.33" W). The field has historically been under a conventional tillage system with no cover crop. Peanuts (*Arachis hypogaea L.*), corn, and cotton were the cash crop, with peanuts being the cash crop in 2019. The soil at the study site is a loamy sand (84.28 % sand, 1.56 % silt, 14.16 % clay), classified as a Fine-loamy, kaolinitic, thermic Plinthic Kandiudults (Soil Survey Staff, 2022). The climate in Tifton is characterized as subtropical with annual average daily maximum, mean, and minimum air temperatures of 25.2 °C, 19.0 °C, and 12.7°C, respectively, and an annual rainfall of 1,208 mm (AEMN, 2023). Table 2.1 shows the temperature and rainfall conditions at the experimental site during the study period.

2.2.2. Experimental Approach

The experiment entailed the integration of cover crop and organic amendment into conventional and strip tillage systems. The management systems served as the experimental treatments, and they were (a) conventional tillage (CT), (b) conventional tillage integrated with cover crops and organic amendments (CT+Int), (c) strip tillage (ST), and (d) strip tillage integrated with cover crops and organic amendments (ST+Int). The experiment was set as a randomized complete block design with four replications, and the size of each experimental plot was 3.66 m × 9.14 m.

Cereal rye was used as the cover crop, and it was planted in the fall of each year at a seeding rate of 101 kg ha^{-1}. It was terminated in the spring by spraying with glyphosate [isopropylamine salt of N-(phosphonomethyl) glycine]. Animal manure (cattle manure in 2020 and broiler litter in 2021 and 2022) and biochar constituted the organic amendments. The cattle manure was obtained from the Animal Science Farm of the University of Georgia Tifton Campus, and the broiler litter was obtained from a local farm (Powell Poultry Farms, LLC), which was about 10 miles from the experimental site. In 2020, the biochar was obtained from Cool Planet based in Greenwood Village, CO, and in 2021 and 2022, the biochar was obtained from Wakefield BioChar based in Valdosta, GA. Corn cobs and stalks were the feedstock of the biochar used in 2020, and pine wood waste was the feedstock of the biochar used in 2021 and 2022. The chemical properties of the animal manure and biochar are presented in Table S2.1. Wakefield BioChar prepares the biochar under 600 ^{o}C pyrolysis temperature, and the biochar has a pH of 10.7. The animal manure and biochar were surface broadcast before tillage at an equal rate of 2.24 Mg ha^{-1} in 2020 and 2021, and 4.48 Mg ha^{-1} in 2022. This resulted in the organic amendment having a C:N ratio of 38.8 in 2020, 26.7 in 2021, and 27.1 in 2022. During tillage, the conventional tillage plots were first tilled by the use of a harrow and a field cultivator. After that, a strip-tillage implement was run across all plots. The strip-tillage implement was equipped with coulters and row cleaners for cutting and raking residues, subsoil shanks for deep ripping of soils, hill disc to fill the ripped slot, roller-crimper attachment to lay down the rye cover as mulch, and cultipacker wheels to break clods and firm the soil.

Stoneville® cotton variety ST 4550 GLTP was planted at 107,639 seeds ha^{-1}, using 0.9 m row spacing, in the spring of each year. To avoid continuous cotton production but be able to evaluate the effects of the various management practices on cotton every year, the study was duplicated on an adjacent field to have another crop in rotation. The other crops in rotation were soybean [*Glycine Max* (L.) Merr.] in 2020, peanut in 2021, and corn in 2022. The plots were irrigated in 2020 and 2021, using a hose reel traveler irrigation system, but were under rainfed conditions in 2022. All plots received the same inorganic fertilizer following the recommendation of the University of Georgia Agricultural and Environmental Services Laboratories (UGA-AESL) to achieve Ro of cotton lint yield in 2020 and 2021 (irrigated conditions), and 1120 kg ha^{-1} in 2023 (rainfed condition). All of P, K, S, and B were applied at pre-plant while 33 % of N was applied at pre-plant and the remaining 67 % was applied at the square stage. The inorganic fertilizer rates applied are presented in Table S2.2. Weed and insect pest control, as well as the use of growth regulators and defoliants, followed standard recommendations by the University of Georgia Cooperative Extension (Hand et al., 2021, 2022).

2.2.3. Data Collection

2.2.3.1. Soil health assessment

Soil health assessment was conducted every spring before termination of cover crops and land preparation for planting cotton, except for soil resistance to penetration (SRP) which was measured before and after tillage operations in spring 2023. The SRP was not measured in 2020 due to experimental limitations. Spring soil health assessment reflects a more stable and inherent state of the soil (Sintim et al., 2019). Soil resistance to penetration was measured 15 cm away from the plant rows and within the top 0-30 cm at an interval of 2.5 cm at four insertions per plot with a penetrometer (FieldScout SC 900 Meter, Spectrum Technologies, Aurora, IL, USA). Water infiltration was measured with a double-ring infiltrometer (Turf-Tech International, Tallahassee, FL, USA) at three replicates per plot. Bulk density within 0-15 cm and 15-30 cm depths was measured with a 5.08 cm bulk density sampling kit (AMS Inc., American Falls, ID).

Composite soil samples were collected from 0-15 cm and 15-30 cm depths, air dried, grounded, and sifted with a 2-mm sieve for chemical and nutrient analyses. Soil respiration was measured following 24-hour incubation with a CO_2 gas analyzer (LI-850, LI-COR Biosciences, Lincoln, NE). Organic matter was analyzed by the loss on ignition method and soil pH was measured in a 1:1 soil water ratio (Crouse et al., 2014). Available nutrients (P, K, Mg, Ca, S, B, Zn, Mn, Fe, Cu) were analyzed with an inductively coupled plasma optical emission spectrophotometer (PerkinElmer® Avio 200 Cross-Flow ICP-OES) after Mehlich-III extraction (Crouse et al., 2014). Available N (NO_3-N and NH_4-N) were analyzed by Waters Agricultural

Laboratories, Inc., Camilla, GA, with an automated flow injection analysis system (FIAlyzer-1000, FIAlab Instruments, Inc., Seattle, WA, United States) after extraction in a 2 M KCl solution.

2.2.3.2. Crop Data Collection

The aboveground biomass of the cover crop and winter weeds was determined from a 1 m^2 area in the spring before termination by herbicide application. The samples were oven-dried at 78 *°C* until constant weight, and the weights were used to calculate biomass accumulation. Cotton was harvested mechanically by sampling seed cotton (lint + seeds) from the entire two middle rows of every plot with a cotton picker. The seed cotton samples were ginned at the University of Georgia Micro Gin in Tifton, GA to determine the gin turnout, which was used to calculate the lint and cottonseed yields. Also, the residual biomass of cotton was determined within a 1-m long strip from every plot. Cotton lint samples were shipped to the USDA classing office in Macon, GA to measure fiber quality parameters [fiber length, fiber strength, micronaire, uniformity, reflectance (Rd), and yellowness (+b)] following standard protocols (Cotton, 2018).

2.2.4. Statistical Analyses

Soil and crop data were analyzed with a linear mixed model using the “lme4" package in R (Pinheiro et al., 2018). For all soil data analyses, except water infiltration, management systems and soil depth were considered fixed effects and the block was a random effect. For water infiltration, cover crop biomass, and cotton productivity and quality parameters, management systems were considered as fixed effects and the block was a random effect. The data were analyzed separately for each year. Homoscedasticity of variance and normality of residual assumptions were tested and appropriate transformations with square root or Box-Cox transformation were performed as needed. Means generated from the analysis were separated using the least square means and adjusted Tukey multiple comparison procedure with the "emmeans" package in R software (Lenth et al., 2022). The significance level of all analyses was assessed at $P = 0.05$.

The SRP data was subjected to cluster analyses using the K-means clustering method. The algorithm of Hartigan and Wong (Hartigan and Wong, 1979) was used and the number of clusters was based on assessing the sums of squares of the cluster solutions and visualized with scree plots. After, hierarchical clustering analyses, employing the complete agglomeration method and Euclidean distance, were used to partition the samples into various groups

2.3. Results and Discussion

2.3.1. Soil properties

The *p*-values of the main effects of management systems and soil depth and their interaction effects on soil properties are reported in Table S2.3. The interaction effects of management systems and soil depth were only significant on B in 2020, organic matter in 2021, and Mn and Cu in 2023. The main effects of management systems on water infiltration were significant in all years. The main effects of management systems were not significant on bulk density in all years. The main effects of management systems were significant on soil respiration in 2022 and 2023, and on organic matter and soil pH in 2022. The main effects of management systems on soil nutrients were significant in a few instances: Cu in 2021; available N (NO_3-N + NH_4-N), Mg, Ca, and Mn in 2022; and on Mn and Cu in 2023.

2.3.1.1. Soil resistance to penetration

The effects of management systems on SRP are shown in Figure 2.1. In general, SRP greater than 2 MPa indicates that the soil is compacted or root growth will be restricted (Duiker, 2002; Moebius-Clune et al., 2016; Sintim et al., 2021). Based on the 2 MPa threshold, the SRP measured in spring 2022 (before tillage) showed soil compaction at 15 cm depth under CT, 12.5 cm depth under CT+Int and ST, and then at 7.5 cm depth under ST+Int (Figure 2.1a). The cluster analyses of the SRP measured in spring 2022 showed the treatment plots can be categorized into three main groups, with all ST plots assigned to one group, all CT plots to another group, and all the CT+Int and ST+Int plots to one group (Figure 2.1b). Overall, the integration of CC and OA increased the SRP under both conventional and conservation tillage systems. The increased SRP could be due to physical impedance by the cereal rye root matrix. Soil health assessment was conducted before cover crop termination and tillage operations in 2022.

In spring 2023, the SRP measured before tillage showed soil compaction at 22.5 cm depth under CT, 15 cm depth under CT+Int, and 12.5 cm depth under ST and ST+Int (Figure 2.1c). The cluster analyses categorized the treatment plots into five main groups (Figure 2.1d). Three replicates of the CT and ST were categorized into one group (brown-colored cluster), with just one replicate of the ST+Int classified into that same group. Also, three replicates of the CT+Int were classified into one group (blue-colored cluster). In general, it can be inferred from the cluster analyses of the SRP measured before tillage in 2023 that there were marginal differences between the CT and ST, but they were substantially different from the CT+Int and ST+Int. Also, the CT+Int was substantially different from the ST+Int.

After tillage in spring 2023, the measured SRP showed soil compaction at 27.5 cm depth under CT, at 30 cm depth under CT+Int, at 10 cm depth under ST, and at 15 cm under ST+Int (Figure 2.1e). Overall, the tillage operations minimized soil compaction. Also, the cluster analyses categorized the treatment plots into three main groups (Figure 2.1f). All samples in the black-colored cluster were either ST or ST+Int, whereas all samples in the green-colored cluster were all CT or CT+Int. Therefore, the results reflect major differences between the tillage operations, with conventional tillage resulting in lower SRP than strip tillage. This was expected because conventional tillage provides the immediate benefit of loosening the soil and promoting root growth (DeLaune et al., 2019; Claassen et al., 2018). Prolonged use of conventional tillage can, however, disrupt soil structure and result in soil compaction (Jabro et al., 2009; Franklin and Bergtold, 2020). In general, it can be seen that the integration of CC and OA under the strip tillage system tended to reduce the SRP measured after tillage, especially at lower depths (Figure 2.1e). The results are consistent with those of Adeli et al. (2019) who found reduced SRP with the inclusion of winter wheat (*Triticum aestivum* L.) cover crop and poultry litter in a no-tillage system. Villamil et al. (2006) also found decreased SRP under no-tillage and cereal rye systems. At the time of taking the penetrometer readings, the cereal rye residue had physically cushioned the soil, which likely conserved soil moisture and concomitantly minimized soil compaction.

2.3.1.2. Water infiltration and bulk density

Figure 2.2 shows the impact of management systems on water infiltration and bulk density. Averaged across the management systems, the water infiltration was 7.64 m day^{-1} in 2021, 10.4 m day^{-1} in 2022, and 10.6 m day^{-1} in 2023. In 2021 and 2023, CT and ST had similar water infiltration, but in 2022, CT had significantly higher infiltration than ST (Figure 2.2b, c). Integration of rye cover crop and organic amendments into CT system (CT+Int) significantly increased water infiltration in 2021 and 2023 compared to CT. The ST+Int significantly increased infiltration only in 2021 compared to the ST. DeLaune et al. (2019) reported an increased water infiltration under no-tillage and cereal rye systems. In general, the integration of CC and OA into the CT improved water infiltration better than the integration into the ST. The synergistic effect of the conventional tillage, cereal rye, and organic amendments increased the soil organic matter which possibly accounts for the increased water infiltration (Figure 2.3d, e, f). Increased water infiltration has been associated with soil organic carbon (Blanco-Canqui and Benjamin, 2013). The management systems had no significant effects on bulk density and there was no consistent trend observed. On average, the bulk density was lower at 0-15 cm soil depth compared to the 15-30cm (Figure 2.2d, e, f). The soil at the experimental site is an Ultisol, which has sandy topsoil and clay at the sublayer

(Adams et al., 2019; Amissah, Ankomah, Lee, Sohag, et al., 2024). Lower organic matter content at the 15-30 cm soil depth could also explain the increased bulk density (Figure 2.3d, e, f).

2.3.1.3. Soil Respiration, Organic Matter, and Soil pH

Significant differences in soil respiration between the management systems were observed within the 0-15 cm depth in 2022 and 2023. Compared to the ST, the CT+Int had greater soil respiration within the 0-15 cm depth in 2022. Also, compared to the ST, the CT+Int and ST+Int had greater soil respiration within the 0-15 cm depth in 2023. The incorporation of cereal rye residue and the organic amendments under CT+Int may have facilitated more microbial activity compared to the ST+Int where there was no incorporation (Wen et al., 2019). In general, the integration of CC and OA under both conventional and conservation tillage systems increased soil respiration. The effects were significant within the top 0-15 cm in 2023. Soil respiration for ST+Int was about 70% greater compared to ST. Our result is congruent with Gong et al. (2022) and Mitchell et al. (2017) who observed increased soil respiration with the inclusion of cereal rye cover crop and organic amendments. Soil respiration is a measure of microbial activity, and thus, the integration of cover crop and organic amendments supplied carbon and nutrient sources that increased the mineralization potential of the soil (Mitchell et al., 2017; Shahzad et al., 2019b; Gong et al., 2022; Sintim et al., 2022a; b).

Generally, the soil respiration was higher at the 0-15 cm soil depth compared to the 15-30 cm. This was expected because there is generally more organic matter within the topsoil which serves as a food source for soil microorganisms (Shahzad et al., 2019b; Franzluebbers, 2021). Increased soil organic matter provides more substrate for microbial activity and consequently increases soil respiration (USDA-NRCS, 2014).

Overall, organic matter within the 0-15 cm soil depth was greater in the CT+Int and ST+Int than the CT and ST, respectively (Figure 2.3d, e, f). However, the differences were statistically significant between the CT and CT+Int in just 2022, with the CT+Int having 25.6% more organic matter when compared to the CT. Increased organic matter following the inclusion of cereal rye, poultry litter, and biochar has been reported in other studies (Nyakatawa et al., 2001; Adekiya et al., 2019; Pinnamaneni et al., 2022; Bista et al., 2019). The organic matter ratio was calculated by dividing the organic matter within the 0-15 cm soil depth to that within the 15-30 cm soil depth. Compared to CT, the CT+Int had significantly greater organic matter stratification within the 0-15 cm soil depth in 2022 (Tables S2.4 and S2.5). A similar trend was observed in 2023, but the differences were not statistically significant. Also, in 2023, the ST+Int tended to have greater organic matter stratification than the ST, but the differences were not statistically significant. The results suggest the cover crop, animal manure, and biochar, which are sources of organic matter, were mainly incorporated within the 0-15 cm soil depth under both tillage systems.

The management systems had a minor impact on soil pH, except in 2022 where the CT+Int had higher soil pH within the 15-30 cm soil depth compared to all the other management systems (Figure 2.3g, h, i). The soil pH within the 15-30 cm in 2022 was 6.4 for CT+Int compared to 6.08, 6.18, and 6.17 for CT, ST, and ST+Inc, respectively. Overall, the soil pH tended to be greater within the 0-15 cm depth than the 15-30 cm depth. Averaged over management systems, the soil pH was 6.43 vs. 6.01 in 2021; 6.52 vs. 6.01 in 2022, and 6.37 vs. 6.08 in 2023 (soil pH within the 0-15 cm depth vs. soil pH within 15-30 cm depth). The experimental site has an Ultisol soil order, with a top sandy layer, and clay-enriched subsoil with a base saturation of less than 35% (Adams et al., 2019; Amissah, Ankomah, Lee, Sohag, et al., 2024b), which could partly explain the differences in soil pH with depth.

2.3.1.4. Soil Nutrients

Significant differences between the management practices were observed in a few soil nutrients (Table 2.2 and S2.3). In 2022, available N within the 0-15 cm soil depth for CT+Int plots was significantly greater than the CT. Other studies reported increased available N concentration with the addition of cereal rye cover crop and poultry litter (Sainju et al., 2006; Adeli et al., 2019). Generally, the available N for all the management systems in the three years was quite low (<10 mg kg^{-1}). Nitrogen is volatile and has several loss pathways which likely explains the low available N, especially as the assessment was made in the spring (Nevins et al., 2020). The concentration of P, K, S, B, Zn, and Fe did not differ significantly between the management systems in all years.

In 2022, CT+Int had greater Mg and Ca levels within the top 0-15 cm depth than CT. Also, compared to CT, the CT+Int increased the Mn level within the 15-30 cm soil depth in 2022 and 2023. In 2023, the ST+Int had a greater Mn level within the 15-30 cm depth than the ST. The Cu level within the 15-30 cm soil depth in 2021 and 2023 was higher under the ST+Int compared to the ST. In the integrated systems, we expected nutrient release from the animal manure, and subsequent retention of the nutrients in the soil by the biochar, to increase the soil nutrient levels (Mitchell and Tu, 2006; Tewolde et al., 2011; Shahzad et al., 2019a). In contrast, we expected nutrient uptake by the cover crop to lower the soil nutrient levels because the soils were sampled for nutrient analyses before terminating the cover crops. Nutrient release from the animal manure, and subsequent retention of the nutrients in the soil by the biochar, may have had dominant effects. This is because there was no instance where the CT and ST had significantly greater nutrient levels than the CT+Int and ST+Int, respectively. However, there were instances where the CT+Int and ST+Int had significantly greater nutrient levels than the CT and ST, respectively.

Nutrient stratification was assessed based on the nutrient ratio, calculated by dividing the nutrient concentration within the 0-15 cm soil depth to that within the 15-30 cm soil depth. There were significant management effects on the stratification ratio of N, P, B, and Zn in 2021, on Zn in 2022, and on Mn in 2023 (Table S2.4). In 2021, the ST+Int had a higher N ratio than the CT and ST, with the CT+Int being intermediate (Table S2.5). The N ratio under CT and ST was less than 1, indicating N leaching under those systems. In contrast, the N ratio under CT+Int and ST+Int were greater than 1, indicating the increased N supplied from the organic amendment was not well distributed across the soil profile. In 2021, the P and Zn ratios tended to be greater under the CT and ST than under the CT+Int and ST+Int, whereas the B ratio tended to be greater under the CT+Int and ST+Int than under the CT and ST. In 2022, the Zn ratio was highest under the ST+Int and least under the CT, and the difference was statistically significant. However, in 2023, the Zn ratio was highest under the CT and least under the ST+Int, but the difference was not statistically significant. Significant differences between management systems were observed for the Mn ratio in 2023, with the Mn ratio being highest under the CT and least under the ST+Int.

The nutrient ratios in 2022 and 2023 tended to be higher than those in 2021, except for the Fe ratio. For instance, averaged over the management systems, the N ratio was 0.84 in 2021, 2.51 in 2022, and 2.22 in 2023. The P ratio was 1.24 in 2021, 1.81 in 2022, and 1.85 in 2023. The K ratio was 1.06 in 2021, 1.82 in 2022, and 1.14 in 2023. The results could partly be linked to the bulk density of the soil, where the bulk density was 1.59 g cm^{-1} in 2021, 1.28 g cm^{-1} in 2022, and 1.49 g cm^{-1}. The nutrient analyses were based on concentration; thus, the increased mass of soil per unit volume may have led to nutrient dilution in the soil. The soil mineral is dominated by oxides of Fe and Al (USDA-NRCS, 2023; Amissah, Ankomah, Lee, Perry, et al., 2024); thus, the dilution effect may have been marginal on the available Fe concentration measured.

2.3.2. Cover crop and winter weeds aboveground biomass

The management systems had significant effects on the aboveground biomass in all years (Table S2.6). The CT+Int and ST+Int produced greater biomass compared to CT and ST (Figure 2.4a, b, c). Winter weed biomass was collected from CT and ST plots (Figure S2.1). This accounts for the significant difference in the biomass. Biomass accumulation for CT+Int was not significantly different from ST+Int, which is consistent with the results of a previous study (Schomberg et al., 2006). On average, the cover crop biomass accumulated in 2021 and 2023 from the CT+Int and ST+Int was about 5 times that of 2022. The cash crop to be planted in 2022 was corn which has an earlier planting date than cotton. Corn is typically planted in March while cotton is planted in late April or early May in south Georgia where the research was conducted (Roth et al., 2023; Hand et al., 2023). In 2022, we collected cover crop biomass in the first week of March while in 2021 and 2023, sampling was done in the middle of April. Cover crop biomass sampling time explains the huge difference in the biomass accumulated. The high biomass accumulation of cereal rye makes it a good carbon input cover crop (Sainju et al., 2007; Finney et al., 2016; Shahzad et al., 2022).

2.3.3. Cotton productivity and quality

The management systems had no significant impact on cotton productivity, except for the gin turnout in 2021 (Table S2.6, Figure 2.5). The gin turnout for ST+Int was significantly greater than CT but was not significantly different from CT+Int and ST. Averaged across all management systems, the lint yield was 1.65 Mg ha^{-1} in 2020, 1.66 Mg ha^{-1} in 2021, and 1.11 Mg ha^{-1} in 2022. The low yield recorded in 2022 was likely due to water stress as cotton was under rainfed conditions. Our results are contrary to previous studies that found an increase in cotton lint yield with the inclusion of CC and OA (Adeli et al., 2019; Reddy et al., 2004; Tewolde et al., 2007; Tewolde et al., 2009). The inorganic fertilizer applied in our study may have provided all nutrients required by cotton and the additional nutrients from the animal manure did not translate into increased yield. The similar yield recorded for CT and ST indicates that the increased soil resistance to penetration under ST (Figure 2.1) was not severe enough to impact the yield of cotton and that strip tillage was effective in preparing the seedbed. Cotton has poor seedling vigor, which when coupled with poor soil structure or compacted soil, can adversely affect plant establishment and consequently result in yield decrease (Snider et al., 2016; Maeda et al., 2023).

The management systems had no significant impact on the cotton fiber quality parameters, except for the micronaire in 2021 (Table S2.6). In general, the micronaire was higher with the integration of CC and OA, with the effect being significant for ST+Int when compared to ST (Table 2.3). Higher micronaire is an undesirable cotton fiber quality attribute (Chakraborty et al., 2000; Amissah et al., 2023). However, the overall magnitude of the differences in fiber quality indicators between the management systems was small and did not affect the grading class.

2.4. Conclusions

Differences in SRP between the conventional and strip tillage systems were observed when measurements were made before tillage in spring 2022 and after tillage in spring 2023, but not before tillage in spring 2023. Also, the integration of cover crops and organic amendments increased the soil depth to compaction zones under the different tillage systems in spring 2023 (both before and after tillage) but the opposite trend was observed in spring 2022 (before tillage). In general, the integration of cover crops and organic amendments tended to increase soil respiration, organic matter, and available nutrients, but the effects were not consistent across years and soil depth. For instance, the integration of cover crops and organic amendments significantly increased soil respiration within the 0-15 cm soil depth under just the strip tillage system in 2023. Also, the integration of cover crops and organic amendments significantly increased soil organic matter within the 0-15 cm soil depth under just the conventional tillage system in 2022. While a similar trend was observed under both the conventional and strip tillage systems in 2023, the differences were not statistically significant. Despite differences in the various soil health properties, the management systems had minimum impact on cotton productivity and fiber quality. The findings indicate that the strip tillage was effective in preparing the seedbed and that the differences in soil properties were not at yield-limiting levels within three years of the study. Moreover, the inorganic fertilizer applied met the nutritional needs of the crop as the additional nutrients from the animal manure did not translate into increased cotton productivity.

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Tables

Table 2.1: Average minimum, mean, and maximum air temperatures and rainfall recorded annually during the study period.

Year	Minimum Temperature	Mean Temperature	Maximum Temperature	Rainfall
	------------------------ °C	-------------------------		Mm
2020	14.7	20.2	25.7	1238
2021	14.0	19.6	25.2	1547
2022	13.7	19.6	25.5	1079
2023	14.1	19.6	25.2	1262

Table 2.2: Impacts of management systems on soil nutrients within 0-15 cm and 15-30 cm soil depth in 2021, 2022, and 2023.

Management system	Avail. N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
	mg kg^{-1}										
	2021 (0-15 cm soil depth)										
CT	6.40±1.10a	116±8a	82.6±4.6a	29.6±1.9a	380±46a	6.12±0.60a	0.43±0.03a	4.13±0.70a	34.5±2.3a	90.3±8.1a	8.95±1.00a
CT+Int	8.16±1.18a	102±12a	61.9±9.5a	29.8±2.4a	363±44a	6.59±0.96a	0.45±0.03a	4.48±0.68a	45.0±3.7a	100.8±8.3a	7.94±1.28a
ST	6.79±0.37a	114±12a	69.7±4.0a	37.8±4.2a	413±45a	7.37±0.59a	0.43±0.02a	3.90±0.66a	35.9±4.5a	92.8±4.8a	7.73±1.11a
ST+Int	8.91±1.91a	120±18a	78.1±16.5a	36.3±4.5a	356±30a	6.66±0.62a	0.44±0.03a	4.78±1.30a	44.2±5.5a	98.6±13.2a	9.19±1.43a
	2021 (15-30 cm soil depth)										
CT	8.77±2.04a	71±9a	62.9±6.5a	24.0±1.6a	283±26a	14.23±1.39a	0.45±0.02a	7.10±1.68a	34.2±1.6a	74.1±3.8a	8.79±1.27ab
CT+Int	9.11±0.79a	99±17a	69.6±13.1a	26.4±2.0a	360±23a	12.15±1.54a	0.37±0.01a	8.71±1.71a	41.7±6.8a	83.7±12.9a	9.70±1.25ab
ST	9.76±0.63a	80±3a	71.2±8.3a	25.4±3.3a	314±32a	10.99±1.63a	0.42±0.01a	4.06±0.61a	34.0±7.2a	75.6±4.9a	8.19±0.77a
ST+Int	8.37±1.16a	114±13a	71.7±15.0a	29.0±2.6a	355±50a	12.21±2.10a	0.37±0.03a	8.57±2.87a	36.2±4.7a	86.9±8.4a	10.17±1.36b
	2022 (0-15 cm soil depth)										
CT	2.58±0.39a	174±15a	97.9±5.2a	43.8±1.9a	501±33a	11.04±0.68a	0.44±0.03a	6.00±0.68a	29.6±2.0a	80.7±2.2a	10.13±0.62a
CT+Int	4.84±1.11b	151±13a	96.9±15.6a	61.2±3.3b	658±32b	10.87±0.97a	0.43±0.03a	6.84±0.33a	33.0±2.2a	76.6±2.0a	10.18±0.83a
ST	2.72±0.49ab	149±18a	115.2±10.8a	44.5±2.6a	475±22a	11.18±0.31a	0.45±0.02a	7.04±1.23a	31.6±1.6a	81.5±5.3a	10.51±0.62a
ST+Int	3.84±0.07ab	170±15a	93.4±7.0a	47.7±4.8a	517±50a	11.02±0.48a	0.46±0.02a	7.20±1.07a	33.2±1.7a	81.7±2.0a	9.87±1.14a
	2022 (15-30 cm soil depth)										
CT	0.64±0.21a	101±4a	55.0±3.8a	13.4±2.2a	233±39a	4.45±0.54a	0.32±0.05a	4.15±0.69a	20.6±1.5a	75.7±1.6a	9.69±0.15a
CT+Int	2.09±0.80a	87±8a	45.5±5.6a	18.5±1.5a	269±30a	3.70±0.23a	0.31±0.01a	4.05±0.29a	26.5±1.2b	73.7±3.5a	9.95±0.65a
ST	0.92±0.46a	89±12a	59.8±4.3a	14.5±0.8a	230±23a	4.01±0.40a	0.32±0.04a	3.84±0.47a	20.8±1.9ab	67.4±5.5a	8.53±1.13a
ST+Int	1.91±0.70a	79±10a	61.9±4.2a	15.6±3.7a	186±15a	3.42±0.39a	0.30±0.05a	2.98±0.29a	23.8±2.1ab	65.9±6.8a	8.56±1.03a

… Continued on next page

Table 2.2 continued…

Management system	Avail. N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
	mg kg^{-1}										
	2023 (0-15 cm soil depth)										
CT	0.90±0.13a	140±17a	113±9a	29.5±2.9a	383±37a	7.64±0.83a	0.40±0.04a	3.64±0.32a	33.6±1.8a	112±9a	8.18±0.65a
CT+Int	1.30±0.28a	142±9a	105±12a	42.8±5.4a	459±46a	8.68±1.13a	0.43±0.01a	4.35±0.85a	37.8±1.9a	109±10a	7.58±0.77a
ST	0.56±0.31a	122±14a	109±11a	35.0±7.4a	395±76a	7.86±2.28a	0.40±0.06a	3.47±0.57a	34.4±4.2a	114±12a	8.15±0.60a
ST+Int	1.49±0.59a	120±10a	102±9a	35.3±5.4a	398±51a	7.79±1.15a	0.40±0.03a	3.83±0.90a	34.4±1.5a	103±6a	8.08±0.99a
	2023 (15-30 cm soil depth)										
CT	0.39±0.26a	61±11a	97±7a	22.6±1.4a	263±7a	9.74±2.76a	0.30±0.01a	2.11±0.21a	23.5±1.0a	86±8a	6.37±1.16a
CT+Int	0.30±0.10a	78±15a	107±4a	23.4±3.0a	261±43a	9.41±1.74a	0.28±0.01a	2.77±0.59a	31.3±3.4b	94±9a	6.82±1.23ab
ST	0.23±0.12a	65±5a	79±5a	21.7±2.9a	258±35a	8.80±1.79a	0.31±0.04a	2.18±0.48a	24.7±1.8a	88±2a	6.35±0.78a
ST+Int	0.99±0.59a	78±7a	93±11a	26.4±8.3a	277±51a	6.99±1.45a	0.31±0.04a	3.32±0.58a	33.0±3.0b	105±12a	8.09±0.60b

Within each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Values represent the mean ± standard error. CT: conventional tillage; CT+Int: conventional tillage with the integration of cover crops (CC) and organic amendments (OA); ST: strip tillage; ST+Int: strip tillage with the integration of CC and OA. Avail. N: available N.

Table 2.3: Management systems impact on cotton fiber quality in 2020, 2021, and 2022.

Management system	Fiber length	Fiber strength	Micronaire	Uniformity	Rd	+b
	Cm	g tex^{-1}		%	%	
			2020			
CT	2.95±0.03a	31.0±0.2a	4.38±0.14a	83.1±0.6a	71.1±2.9a	8.17±0.09a
CT+Int	2.96±0.02a	30.4±0.4a	4.12±0.09a	82.1±0.7a	71.7±1.2a	8.35±0.26a
ST	2.93±0.04a	30.8±0.3a	4.18±0.07a	82.2±0.7a	72.9±1.6a	8.20±0.11a
ST+Int	2.95±0.01a	30.7±0.2a	4.12±0.13a	81.9±0.6a	71.7±2.4a	8.33±0.18a
			2021			
CT	2.87±0.03a	33.0±0.1a	4.70±0.04a	83.8±0.2a	75.9±0.2a	8.20±0.09a
CT+Int	2.88±0.01a	32.8±0.2a	4.85±0.06ab	83.4±0.4a	76.4±0.1a	8.28±0.06a
ST	2.88±0.01a	33.1±0.7a	4.68±0.05a	83.2±0.1a	76.1±0.4a	8.22±0.09a
ST+Int	2.88±0.02a	33.4±0.4a	4.95±0.06b	83.9±0.4a	76.0±0.4a	8.22±0.05a
			2022			
CT	2.92±0.03a	31.2±0.9a	4.30±0.04a	84.5±0.2a	76.1±0.2a	8.68±0.05a
CT+Int	2.92±0.02a	30.6±0.3a	4.42±0.06a	84.1±0.1a	76.0±0.2a	8.90±0.04a
ST	2.91±0.01a	31.5±0.5a	4.42±0.05a	84.5±0.5a	76.2±0.4a	8.68±0.05a
ST+Int	2.91±0.03a	31.4±0.5a	4.42±0.05a	84.4±0.2a	76.3±0.3a	8.82±0.15a

Within each year, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Values represent the mean ± standard error. CT: conventional tillage; CT+Int: conventional tillage with the integration of cover crops (CC) and organic amendments (OA); ST: strip tillage; ST+Int: strip tillage with the integration of CC and OA. Rd: fiber reflectance; +b: fiber yellowness.

Figures

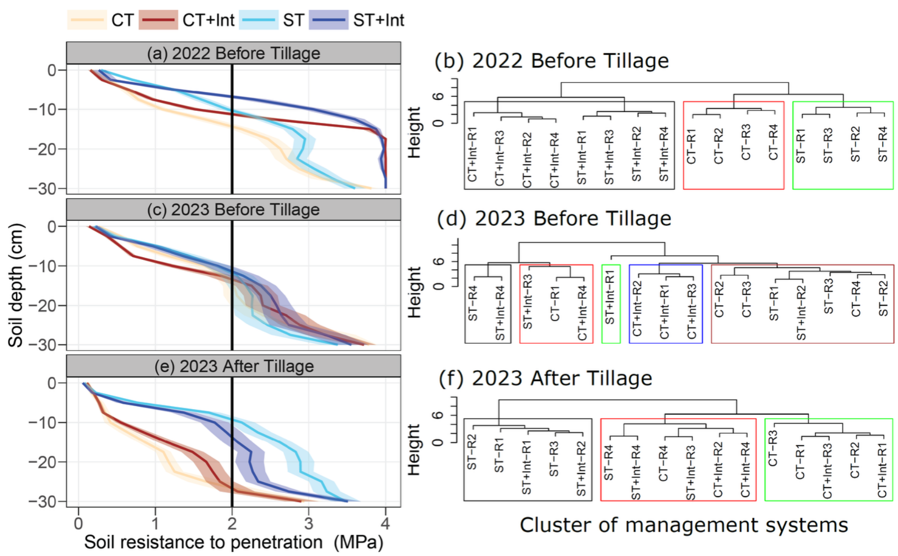

Figure 2.1: Management impacts on soil resistance to penetration before tillage in 2022 (a and b), before tillage in 2023 (c and d), and after tillage operations in 2023 (e and f). Sub-figures a, c, and e are the line graphs of the soil resistance to penetration data, and sub-figures b, d, and f are clusters of management systems derived from cluster analyses. The standard deviation of the mean (n=16) in the line graphs is marked by colored ribbons. Penetration resistance values greater than 2 MPa indicate the soil is compacted or root growth will be restricted, as indicated by the black solid vertical line in sub-figures a, c, and e. The various clusters are differentiated by colored boxes.

CT: conventional tillage; CT+Int: conventional tillage with the integration of cover crops (CC) and organic amendments (OA); ST: strip tillage; ST+Int: strip tillage with the integration of CC and OA. Management treatment names followed by '-R' and a number designate the replication number of the sample.

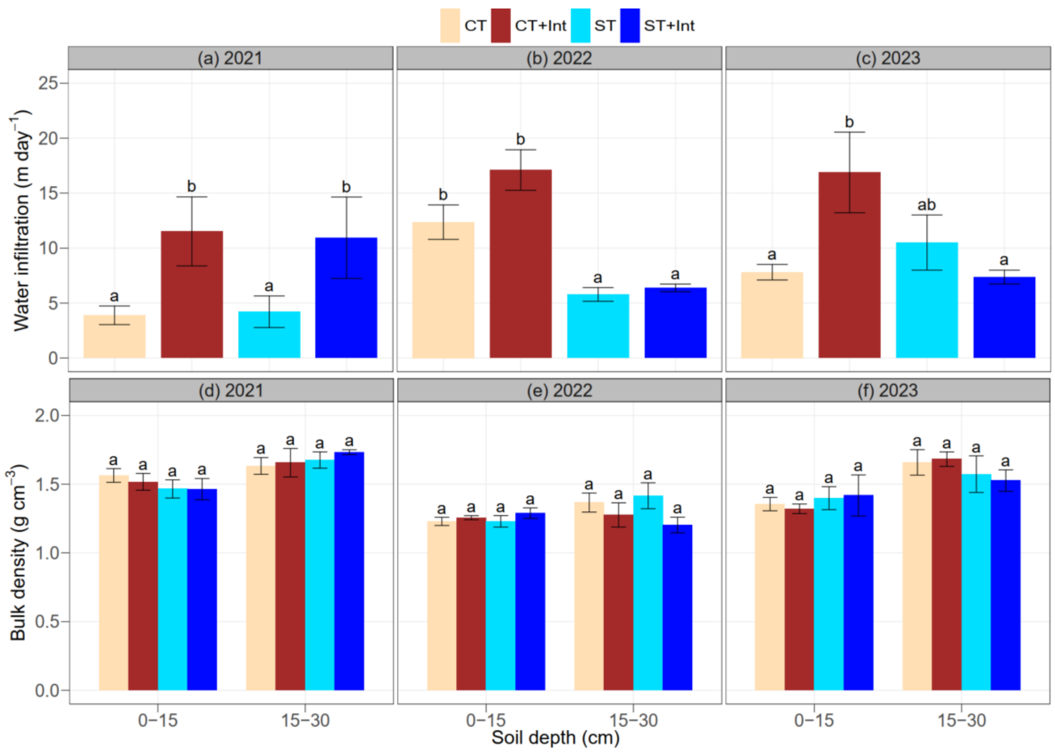

Figure 2.2: Management systems impact on water infiltration (a, b, c) and bulk density (d, e, f) in 2021, 2022, and 2023. Within each depth and year, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Error bars represent standard errors of the mean. CT: conventional tillage; CT+Int: conventional tillage with the integration of cover crops (CC) and organic amendments (OA); ST: strip tillage; ST+Int: strip tillage with the integration of CC and OA.

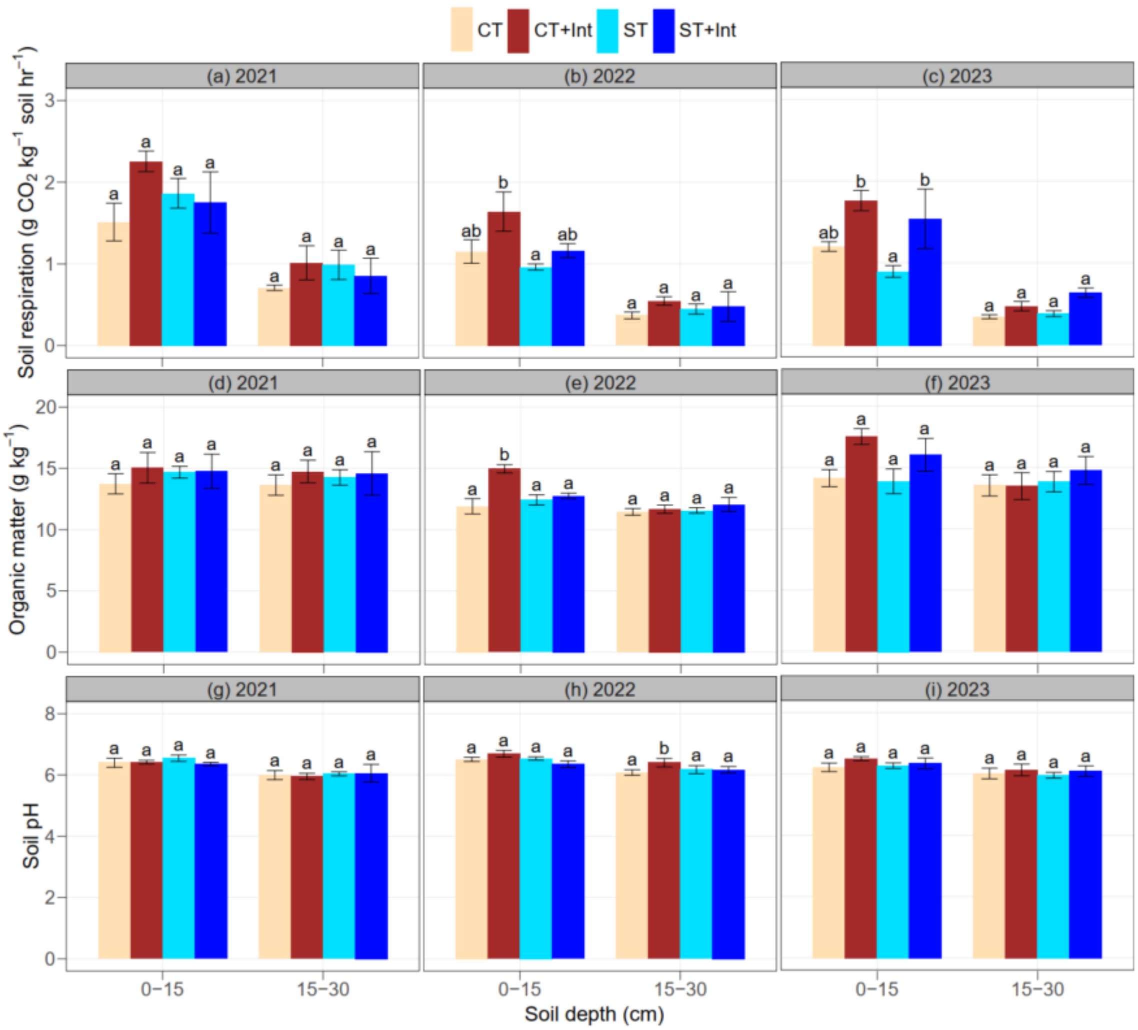

Figure 2.3: Management systems impact on soil respiration (a, b, c), organic matter (d, e, f), and soil pH (g, h, i) in 2021, 2022, and 2023. Within each depth and year, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Error bars represent standard errors of the mean. CT: conventional tillage; CT+Int: conventional tillage with the integration of cover crops (CC) and organic amendments (OA); ST: strip tillage; ST+Int: strip tillage with the integration of CC and OA.

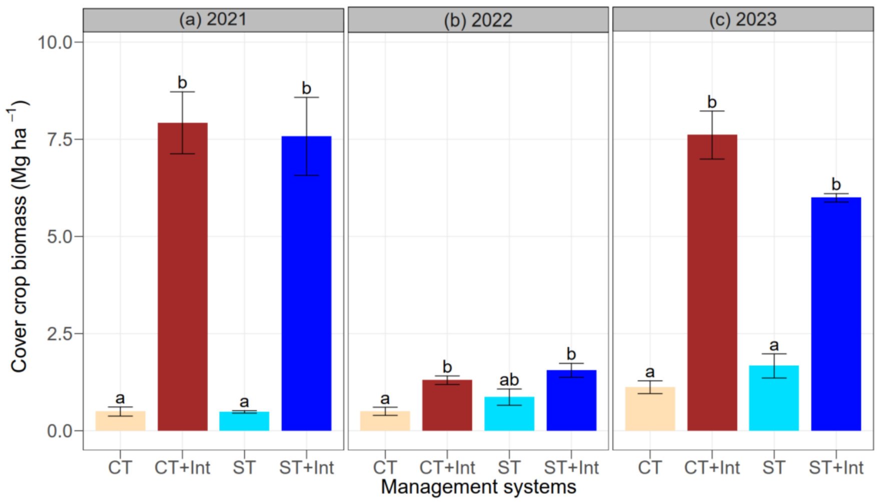

Figure 2.4: Cover crop biomass produced in 2021 (a), 2022 (b), and 2023 (c). Winter weed biomass was collected from CT and ST. Within each year, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Error bars represent standard errors of the mean. CT: conventional tillage; CT+Int: conventional tillage with the integration of cover crops (CC) and organic amendments (OA); ST: strip tillage; ST+Int: strip tillage with the integration of CC and OA.

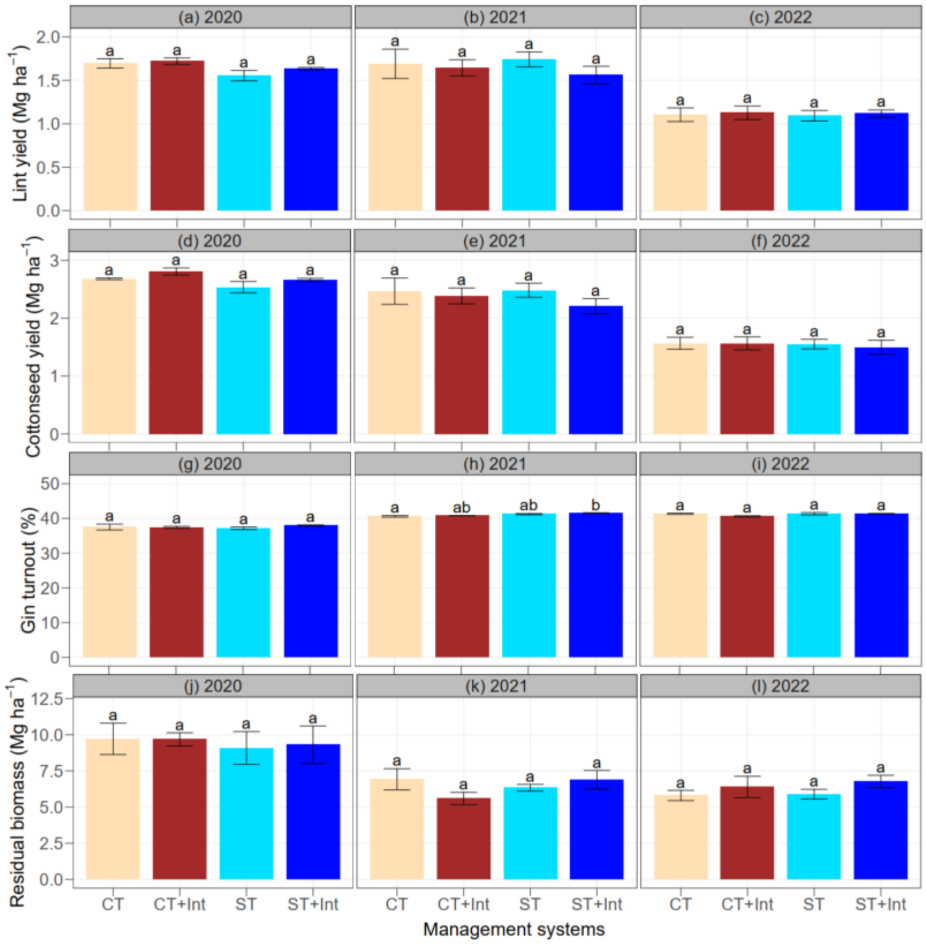

Figure 2.5: Impacts of management systems on lint yield, cottonseed yield, gin turnout, and residual biomass in 2020, 2021, and 2022. Within each year, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Error bars represent standard errors of the mean. CT: conventional tillage; CT+Int: conventional tillage with the integration of cover crops (CC) and organic amendments (OA); ST: strip tillage; ST+Int: strip tillage with the integration of CC and OA.

Supplemental Tables

Table S2.1: Nutrient composition of organic amendments used in the study.

Organic amendment	Total C	Total N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
	---------- $g\ kg^{-1}$ ----------											
	---------- 2020 ----------											
Cattle manure	83.8	10.1	9.84	5.85	3.51	13.1	1.78	0.02	0.8	0.25	23.1	1.05
Biochar	458	3.88	0.7	6.09	0.38	0.75	0.22	0.01	0.02	0.01	0.43	0.06
	---------- 2021 ----------											
Broiler litter	275	39.8	16.5	40.1	9.18	3.52	15.8	0.12	0.37	0.37	4.28	0.49
Biochar	866	2.95	1.77	4.88	3.45	24	0.37	0.25	0.25	0.49	0.86	0.25
	---------- 2022 ----------											
Broiler litter	275	39.1	16.8	39.9	9.2	34.8	15.8	0.12	0.55	0.37	4.46	0.49
Biochar	866	2.95	1.77	4.88	3.45	24	0.37	0.25	0.25	0.49	0.86	0.25

Corn cobs and stalks were the feedstock of the biochar used in 2020, and pine wood waste was the feedstock of the biochar used in 2021 and 2022.

Table S2.2: Rates of inorganic nutrients applied.

Year	N	P_2O_5	K_2O	S	B
	---------- $kg\ ha^{-1}$ ----------				
2020	84.1	89.7	78.5	11.2	0.56
2021	106	112	89.7	11.2	0.56
2022	50.4	89.7	112.1	11.2	0.56

Urea ammonium nitrate solution, diammonium phosphate, potassium chloride, potassium sulfate, and Borosol® 10 solution were used as fertilizer sources.

Table S2.3: *P*-values of the main effects and interaction effects of management systems and soil depth on soil properties in 2021, 2022, and 2023.

Effect	Infiltra-tion	Bulk density	Respira-tion	Organic matter	Soil pH	Avail. N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
	2021															
Management (M)	**0.004**[†]	0.959	0.078	0.286	0.813	0.411	0.355	0.791	0.100	0.812	0.853	0.176	0.065	0.069	0.451	**0.004**
Depth (D)	NA	0.062	**0.011**	0.497	**0.019**	0.309	0.084	0.501	**0.043**	0.148	**0.008**	0.252	**0.034**	0.273	0.059	0.152
M × D	NA	0.383	0.719	0.985	0.865	0.481	0.286	0.417	0.326	0.392	0.353	**0.024**	0.221	0.661	0.996	0.113
	2022															
Management (M)	**<0.001**	0.529	**0.029**	**0.001**	**0.044**	**0.011**	0.351	0.180	**0.003**	**0.005**	0.400	0.890	0.909	**0.021**	0.635	0.606
Depth (D)	NA	0.336	**0.003**	**0.013**	**0.021**	**0.027**	**0.003**	**0.005**	**0.001**	**0.001**	**<0.001**	**0.014**	**0.009**	**0.003**	**0.035**	0.160
M × D	NA	0.091	0.168	**0.003**	0.644	0.825	0.546	0.376	0.109	0.126	0.503	0.888	0.419	0.532	0.231	0.566
	2023															
Management (M)	**0.020**	0.957	**0.009**	0.095	0.424	0.159	0.573	0.479	0.557	0.853	0.802	0.999	0.301	**<0.001**	0.88	**0.052**
Depth (D)	NA	0.096	**0.004**	0.086	0.062	0.051	**0.006**	0.157	**0.044**	**0.022**	0.627	0.064	**0.043**	**0.006**	**0.036**	**0.02**
M × D	NA	0.276	0.133	0.113	0.934	0.839	0.513	0.317	0.636	0.814	0.891	0.611	0.708	**0.009**	0.14	**0.041**

[†] Bold texts indicate significant effect terms ($P < 0.05$). Avail. N: available N.

Table S2.4: *P*-values of the main effects of management systems on stratification ratio of organic matter and soil nutrients in 2021, 2022, and 2023.

Year	Organic matter ratio	N ratio	P ratio	K ratio	Mg ratio	Ca ratio	S ratio	B ratio	Zn ratio	Mn ratio	Fe ratio	Cu ratio
2021	0.856	**0.012**	**0.032**	0.284	0.439	0.143	0.143	**0.041**	**0.016**	0.677	0.993	0.129
2022	**0.025**	0.403	0.466	0.362	0.959	0.372	0.367	0.771	**0.022**	0.380	0.137	0.377
2023	0.115	0.435	0.214	0.134	0.66	0.610	0.284	0.821	0.341	**0.022**	0.071	0.070

† Bold texts indicate significant effect terms ($P < 0.05$).

Table S2.5: Impacts of management systems on stratification ratio of organic matter and soil nutrients in 2021, 2022, and 2023.

Management system	Organic matter ratio	N ratio	P ratio	K ratio	Mg ratio	Ca ratio	S ratio	B ratio	Zn ratio	Mn ratio	Fe ratio	Cu ratio
						2021						
CT	1.01±0.03a	0.68±0.20a	1.69±0.19b	1.36±0.18a	1.25±0.08a	1.36±0.18a	0.44±0.06a	0.98±0.10a	0.64±0.11ab	1.01±0.06a	1.22±0.09a	1.04±0.07a
CT+Int	1.02±0.02a	1.05±0.06ab	1.09±0.13a	0.91±0.06a	1.15±0.12a	1.01±0.11a	0.54±0.02a	1.22±0.06b	0.55±0.08a	1.14±0.16a	1.25±0.14a	0.82±0.07a
ST	1.03±0.02a	0.70±0.06a	1.43±0.13ab	1.03±0.14a	1.53±0.17a	1.34±0.16a	0.56±0.03a	1.02±0.06a	0.95±0.04b	1.17±0.20a	1.24±0.08a	0.94±0.08a
ST+Int	1.04±0.02a	1.21±0.08b	1.18±0.09a	1.20±0.29a	1.39±0.30a	1.03±0.04a	0.58±0.03a	1.21±0.16b	0.53±0.04a	1.31±0.20a	1.23±0.04a	0.82±0.06a
						2022						
CT	1.04±0.05a	3.27±0.73a	1.72±0.09a	1.80±0.11a	3.54±0.57a	2.29±0.29a	2.54±0.19a	1.49±0.22a	1.51±0.16a	1.44±0.04a	1.07±0.04a	1.05±0.08a
CT+Int	1.29±0.06b	3.49±1.57a	1.75±0.12a	2.18±0.38a	3.33±0.14a	2.51±0.21a	2.99±0.38a	1.41±0.11a	1.70±0.08ab	1.26±0.13a	1.05±0.06a	1.04±0.12a
ST	1.08±0.05ab	4.36±1.05a	1.70±0.08a	1.95±0.21a	3.09±0.14a	2.14±0.27a	2.86±0.23a	1.47±0.16a	1.81±0.15ab	1.55±0.13a	1.22±0.08a	1.27±0.10a
ST+Int	1.06±0.04ab	1.71±0.39a	2.27±0.37a	1.56±0.23a	3.87±1.30a	2.80±0.27a	3.28±0.16a	1.70±0.27a	2.41±0.25b	1.42±0.12a	1.27±0.10a	1.16±0.09a
						2023						
CT	1.05±0.06a	3.19±1.60a	2.42±0.24a	1.20±0.16a	1.34±0.20a	1.46±0.14a	0.57±0.21a	1.32±0.18a	1.77±0.22a	1.43±0.02b	1.30±0.02a	1.36±0.15a
CT+Int	1.32±0.09a	3.78±1.13a	2.02±0.41a	0.98±0.12a	1.93±0.32a	1.84±0.18a	1.00±0.22a	1.54±0.09a	1.59±0.08a	1.23±0.06ab	1.17±0.07a	1.16±0.09a
ST	1.00±0.04a	6.55±2.70a	1.83±0.03a	1.41±0.24a	1.62±0.31a	1.52±0.14a	0.87±0.12a	1.43±0.40a	1.71±0.32a	1.38±0.07ab	1.29±0.11a	1.31±0.08a
ST+Int	1.11±0.13a	2.88±1.44a	1.63±0.24a	1.11±0.05a	1.79±0.48a	1.61±0.33a	1.30±0.38a	1.33±0.18a	1.20±0.23a	1.07±0.10a	1.01±0.07a	0.99±0.06a

Within each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Values represent the mean ± standard error. CT: conventional tillage; CT+Int: conventional tillage with the integration of cover crops (CC) and organic amendments (OA); ST: strip tillage; ST+Int: strip tillage with the integration of CC and OA.

Table S2.6: *P*-values of the main effects of management systems on aboveground biomass of cover crop and winter weeds, and on cotton productivity and fiber quality from 2020 to 2023.

Season	Cover crop biomass	Lint yield	Cottonseed yield	Gin turnout	Residual Biomass	Fiber length	Fiber strength	Micronaire	Uniformity	Rd	+b
2020/2021	**<0.001**†	0.133	0.103	0.699	0.908	0.805	0.387	0.393	0.625	0.943	0.87
2021/2022	**0.004**	0.789	0.702	**0.019**	0.180	0.938	0.765	**0.005**	0.211	0.764	0.761
2022/2023	**<0.001**	0.719	0.927	0.100	0.535	0.993	0.679	0.272	0.722	0.693	0.195

† Bold texts indicate effect terms (*P* < 0.05). Rd: fiber reflectance; +b: fiber yellowness.

Supplemental Figures

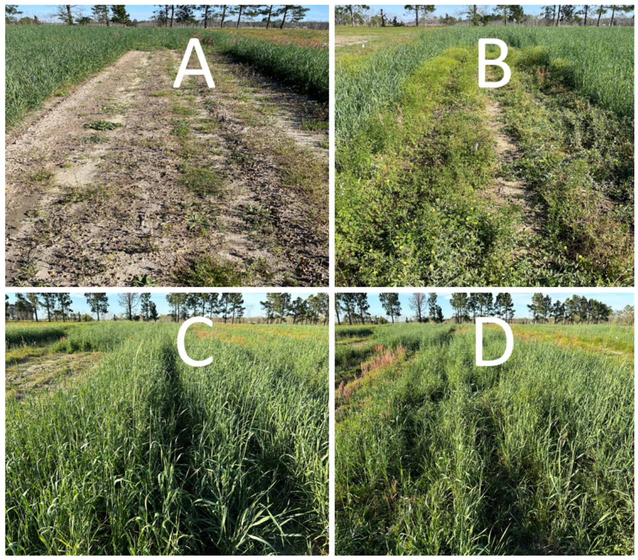

Fig. S2.1: Experimental field plots in spring 2023 showing the various management systems: (A) conventional tillage, (B) strip tillage, (C) conventional tillage with the integration of cover crops and organic amendments, and (D) strip tillage with the integration of cover crops and organic amendments management systems.

CHAPTER 3

IMPACTS OF INTEGRATED SUSTAINABLE MANAGEMENT SYSTEMS ON SOIL BIOLOGICAL AND CHEMICAL PROPERTIES

Ankomah, G., Habteselassie, M. Y., Franklin, D. H., Snider, J. L., Kemerait, R. C., & Sintim, H. Y. (2025). Impacts of integrated sustainable management systems on soil biological and chemical properties.

To be submitted to *Agrosystems, Geosciences & Environment*.

Abstract

Sustainable management practices are crucial to improve soil health and ensure the sustainability of crop production. Integrating different sustainable agricultural practices could help improve soil health better than individual practices. A field study was conducted to evaluate the impact of individual and integrated sustainable management practices on soil biological and chemical properties. The management systems were no sustainable system (Nss; control), reduced tillage (RT), cover crop (CC), cover crop + organic amendments (CC+OA), and cover crop + organic amendments + reduced tillage (CC+OA+RT). The experiment was set up as a randomized complete block design with four replications. Cereal rye (*Secale cereale*) was used as the cover crop and the OA was a combination of animal manure and biochar (applied at an equal rate of 2.24 Mg ha^{-1} in 2020 and 2021, and 4.48 Mg ha^{-1} in 2022). Soil samples were collected in the spring, and soil biological and chemical properties were assessed. The integrated sustainable management systems did not increase the relative abundance and alpha diversity of bacteria. Tillage had a dominant effect on the abundance and alpha diversity of fungi. The RT tended to have higher fungi alpha diversity. In the third year, plots with CC resulted in higher soil respiration, indicating the cover crop had a dominant effect. Overall, the integrated sustainable management systems did not consistently improve the soil biological and chemical properties. Moreover, the addition of biochar to the OA plots may have masked the effect of the CC and the poultry litter.

3.1. Introduction

Soil health deterioration is a major challenge to the sustainability of crop production and poses a serious threat to food security (Lal, 2015; Pozza and Field, 2020; Strauss et al., 2023). With the climate change crisis and the expected increase in world population, there is a pressing need to improve soil health and ensure the sustainability of crop production (Lal, 2015; Pozza & Field, 2020; United Nations, 2019). Soil health deterioration can be attributable to adverse environmental factors and poor soil management practices (Hou et al., 2020). For instance, in tropical and subtropical regions, warm temperatures coupled with frequent and intensive rainfall result in rapid weathering of primary minerals and leaching of base cations (Amissah et al., 2024; Nunes et al., 2019; Pincus et al., 2017). In Georgia, USA, where this study was conducted, the soils are mainly Ultisols, which have poor native fertility and low organic matter. Ultisols are highly-weathered soils and the predominant clay mineralogy is kaolinite, a 1:1 clay type that has low cation exchange capacity (less than 16 $cmol_c\ kg^{-1}$) and low buffering capacity (Amissah et al., 2024; Swaby et al., 2016; Truman et al., 2010).

Besides climatic conditions, soil management practices such as conventional tillage can degrade soil health. Continuous and intensive tillage results in the breakdown of soil aggregates into smaller particles, rendering the soil more susceptible to erosion (Magdoff and Harold, 2021). Extensive tillage also disrupts the composition, abundance, and activities of soil microorganisms (Agyei et al., 2024; Mathew et al., 2012; Nunes et al., 2020). The hyphae characteristics of fungal classes such as Sodariomycetes, Dothideomycetes, and Eurotiomycetes (Wang et al., 2023; Piazza et al., 2019) are susceptible to destruction and functional limitation by intensive tillage (Bonfante and Genre, 2010). Therefore, sustainable management practices are crucial to improving soil health and crop productivity. Soil management practice can be termed as sustainable when the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing the soil functions that enable those services or biodiversity (FAO, 2015). Conservation tillage, cover crops, and organic amendments are sustainable practices employed to enhance soil health.

Individual sustainable agricultural practices have their benefits and limitations. For instance, conservation tillage improves soil properties, especially the physical properties, due to minimal soil disturbance (Franklin and Bergtold, 2020; Nunes et al., 2018). The adoption of conservation tillage such as no-tillage has been documented to reduce costs (Che et al., 2023). There is less fuel usage because of the limited machinery operations. Despite the benefits of conservation tillage, unique challenges emerge when transitioning to a conservation tillage system. Common problems in conservation tillage systems include short-term soil compaction issues, weed pressures, and stratification of mineral nutrients (Franzluebbers, 2002; Siri-Prieto et al., 2007; Wright et al., 2007; Franzluebbers and Stuedemann, 2008; Ankomah et al., 2024).

Integrating different sustainable agricultural practices could help improve soil health better than the adoption of individual practices separately (Sallet, 2020; USDA-NRCS, 2024). Cover crops have received significant attention due to their numerous soil health benefits and could effectively complement conservation tillage systems. Cover crop systems fulfill two of the soil health principles recommended by the USDA-NRCS (2024): maximizing soil cover and maintaining living roots. Soil health benefits of including cover crops in conservation tillage systems have been well-documented (Farmaha et al., 2022; Wallander et al., 2021; Claassen et al., 2018).

Also, including carbon inputs such as animal manure and biochar may further build up soil organic carbon and improve the overall soil health. The application of poultry litter in a no-till cover crop system has been shown to increase soil carbon by 22% (Adeli et al., 2019). A previous study by Nyakatawa et al. (2001) showed that soil organic matter and NO_3-N increased following the application of poultry litter in a cereal rye-conservation tillage system. In their study, they attributed the increase in soil organic matter to less biological oxidation of crop residues and the C contributed by the poultry litter. In a recent study, the integration of cereal rye cover crops and organic amendments (animal manure and biochar) into conservation tillage systems was found to increase soil respiration and organic matter (Ankomah et al., 2024).

The implementation of conservation tillage, cover crops, and organic amendments has the potential to enhance soil health by improving soil respiration and organic matter, promoting biological diversity, and optimizing nutrient cycling (Nyakatawa et al., 2001; Mitchell et al., 2017; Bista et al., 2019; Franklin and Bergtold, 2020; Gong et al., 2022; Ankomah et al., 2024). However, whether a more intensive sustainable system enhances soil health more effectively than a less intensive sustainable system remains unexplored. For instance, cereal rye and biochar are important carbon sources, but the high carbon-to-nitrogen ratio, particularly of the biochar, could lead to nutrient immobilization and disrupt the soil microbial community and activities (Bossolani et al., 2023; Ankomah et al., 2024). Therefore, this study aimed to assess how intensive sustainable management systems compare to less intensive systems in improving soil biological and chemical health.

3.2. Materials and Methods

3.2.1 Site description

The field study was set up at the USDA-ARS Bellflower Farm in Tifton, GA (31°30'32.83" N, 83°33'29.33" W) from 2020 to 2023. The soil at the study site is a loamy sand (84.28 % sand, 1.56 % silt, 14.16 % clay) and classified as a Fine-loamy, kaolinitic, thermic Plinthic Kandiudults (Soil Survey Staff, 2022). Tifton has a subtropical climate with annual average daily maximum, mean, and minimum air temperatures of 25.2 °C, 19.0 °C, and 12.7°C, respectively, and an average yearly rainfall of 1,208 mm (AEMN, 2025). The monthly mean temperature and total precipitation in 2020, 2021, 2022, and 2023 are reported in Table 3.1. The annual average daily mean temperature during experimental years ranged from 19.6 °C to 20.2 °C, whereas the annual total precipitation received during experimental years ranged from 1079 mm to 1547 mm.

3.2.2 Experimental set-up

Single and integrated sustainable management systems were assessed. The management systems were no sustainable system (Nss; conventional tillage), cover crop (CC), reduced tillage

(RT), cover crop + organic amendments (CC+OA), and cover crop + organic amendments + reduced tillage (CC+OA+RT). Treatments CC and RT reflect a single sustainable management system, treatment CC+OA reflects two integrated sustainable management systems, and treatment CC+OA+RT reflects three integrated sustainable management systems. The experiment was set up as a randomized complete block design with four replications. Each experimental plot was 3.66 m × 9.14 m in size. The cover crop (cereal rye) was annually planted in the fall at a seeding rate of 101 kg ha^{-1} and terminated in the following spring with glyphosate [isopropylamine salt of N-(phosphonomethyl) glycine]. Organic amendments utilized in the study were animal manure (cattle manure in 2020 and poultry litter in 2021 and 2022) and biochar.

The cattle manure was provided by the Animal Science Farm of the University of Georgia Tifton Campus, while the broiler litter was acquired from a nearby farm, Powell Poultry Farms, LLC, situated approximately 10 miles away from the experimental location. In 2020, the biochar was obtained from the Cool Planet warehouse in Valdosta, GA. In 2021 and 2022, the biochar was obtained from Wakefield BioChar based in Valdosta, GA. The feedstock used in producing the biochar was corn cobs and stalks in 2020 and pine wood waste in 2021 and 2022. The nutrient composition of the animal manure and biochar are presented in Table S3.1. The animal manure and biochar were surface broadcast manually before land preparation at an equal rate of 2.24 Mg ha^{-1} in 2020 and 2021, and 4.48 Mg ha^{-1} in 2022 (Table S3.2). In the N_{SS}, CC, and CC+OA plots, the initial tillage involved the use of a harrow followed by a field cultivator. Subsequently, a strip-tillage implement was run across all plots. Thus, the RT and CC+OA+RT plots were subject to a one-time strip-tillage operation annually. The N_{SS}, CC, and CC+OA were also harrowed one time after harvest every year. In 2020 and 2021, the plots were irrigated using a hose reel traveler irrigation system while in 2022 they were under rainfed conditions. The field was cultivated to cotton (*Gossypium hirsutum* L.) in 2020 and 2022, and to peanut (*Arachis hypogaea* L.) in 2021. All plots received the same inorganic fertilizer following the University of Georgia Agricultural and Environmental Services Laboratories (UGA-AESL) recommendation. The inorganic fertilizer rates applied are presented in Table S3.3. In 2021, no inorganic fertilizer was applied because the soil test indicated the nutrients were sufficient for growing peanuts. Weed and insect pest control followed recommendations in the production guide for the two crops developed by the University of Georgia Cooperative Extension (Hand et al., 2021; Monfort et al., 2022).

3.2.3 Soil sampling and analyses

Composite soil samples were collected from 0-15 cm depth with a 5.08 cm diameter bulk density sampling kit (AMS Inc., American Falls, ID) before terminating cereal rye and performing tillage operations in the spring of 2022, 2022, and 2023 (Table S3.2). Soil samples were air-dried, grounded, and sifted with a 2-mm sieve for chemical and nutrient analyses. Soil respiration was determined following a 24-hour incubation at 20 °C (Crouse et al., 2014). The CO_2 evolved were measured using a LI-850 gas analyzer (LI-COR Biosciences, Lincoln, NE). Organic matter was determined via the loss on ignition method, while soil pH was measured using a 1:1 ratio of soil to water (Crouse et al., 2014). Available soil nutrients including phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), sulfur (S), boron (B), zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu) were analyzed using an inductively coupled plasma optical emission spectrophotometer (PerkinElmer® Avio 200 Cross-Flow ICP-OES) after Mehlich-III extraction (Crouse et al., 2014). Nitrate-nitrogen (NO_3-N) and ammonium-nitrogen (NH_4-N) were analyzed using an automated flow injection analysis system (FIAlyzer-1000, FIAlab Instruments, Inc., Seattle, WA, United States) after extraction with a 2 M KCl solution.

3.2.4 Soil microbial community characterization

In 2023, soils were sampled and analyzed to assess the third-year impact of the management systems on the soil microbial community. Soil DNA was extracted from 0.25 g of soil per sample using a DNeasy PowerSoil DNA extraction kit following the manufacturer's guidelines (Qiagen, 2018). Subsequently, the extracted DNA was quantified with a Qubit Flex Fluorometer (ThermoFisher Scientific). Soil DNA extracts were sent to LC Sciences, Houston, TX for sequencing. The extracts were processed for iTag amplicon sequencing for taxonomic identification. To create Illumina amplicon libraries (iTags), the extracted samples were amplified using single barcode primers aimed at the V3 and V4 regions of the bacterial 16S rRNA and the ITS region of fungi (Figure S1 and S2; Daum, 2017). The amplified library was sequenced on a NovaSeq platform with 250 bp paired-end reads mode (2 × 250 bp). The raw data files in FASTQ were subjected to reads merge by overlapping sequences, data quality control, and chimera filtering, resulting in high-quality clean data. The Divisive Amplicon Denoising Algorithm

(DADA2) (Callahan et al., 2016) was used for dereplication (equivalent to 100% similarity clustering), and generation of representative sequences at single-base resolution, thereby greatly improving the accuracy of the data and taxonomy resolution. The DADA2 was used to create amplicon sequence variants (ASVs) table (Blaxter et al., 2005). After filtering the chimeras, high-quality data (tags) were counted. The Silva and NT-16S database was used for bacteria taxonomy classification (Quast et al., 2013; Silva, 2019). For fungi taxonomy classification, the Unite database was used (Abarenkov et al., 2024).

3.2.5. Statistical analysis

The soil respiration, organic matter, soil pH, and nutrient data were analyzed as a repeated measure with a linear mixed model using the 'lme4' package in R (Bates et al., 2015). The year was assigned as a within-plot factor variable, management systems as between between-plot factor variable, and block was a random term. The assumptions of normality of residuals, homoscedasticity of variance, and sphericity were tested. Appropriate transformations (Box-Cox and square root methods) and corrections (Greenhouse–Geisser and Huynh–Feldt methods) were applied as needed. Mean separations were performed using the least square means and the adjusted Sidak multiple comparison procedure with the 'emmeans' package in R (Lenth et al. 2025). Bacterial relative abundance and fungal relative abundance at the class level were analyzed with a linear mixed model using the "lme4" package in R, and a stacked bar plot was plotted using the ggplot2 package. Homoscedasticity of variance and normality of residual assumptions were tested.

When necessary, appropriate transformations with the square root or Box-Cox transformation were performed as needed. Mean separations were performed using the least square means and the Sidak comparison procedure with the ‘emmeans’ package in R.

Bacteria relative abundance, fungi relative abundance, and 2023 soil nutrient data were subjected to cluster analyses using the vegan package and “hclust” function in R. Nutrient data were scaled utilizing the column centering and scaling method before performing the cluster analyses (The R Core Team, 2025). The average clustering algorithm method was used for the clustering. Bray-Curtis distance was used for the bacteria and fungi clustering, while Euclidean distance was employed to partition soil nutrients into groups.

Alpha diversity and beta diversity of the bacteria and fungi communities were calculated using the phyloseq package in R. Chao1 was used as the index for the alpha diversity and the beta diversity was based on the Bray-Curtis similarity/dissimilarity distance matrix. Subsequently, the alpha diversity (Chao1) data were analyzed with a linear mixed model using the “lme4" package in R and presented as a box plot using the ggplot2 package. The nonparametric multidimensional scaling (NMDS) analysis was performed for the beta diversity using the “metaMDS” function in R. The test statistics for beta diversity were conducted using the "adonis" function from the vegan package, which performs PERMANOVA (Permutational Multivariate Analysis of Variance). The significance level for all analyses was evaluated at a threshold of $p = 0.05$.

3.3. Results

3.3.1. Bacterial and fungal communities

When averaged across all the management systems, the most abundant bacterial class was Thermoleophilia, followed by Alphaproteobacteria, Actinobacteria, Bacilli, Actinobacteriota, Acidobacteriae, Planctomycetes, Gemmatimonadetes in decreasing order (Figure 3.1A). Significant differences were observed between the management systems for the relative abundance of Thermoleophilia (Table S3.4, S3.5). The Nss had a higher Thermoleophilia abundance compared to the CC+OA. However, the Thermoleophilia abundance for Nss was not significantly higher than the other management systems (RT, CC, and CC+OA+RT). Also, the Thermoleophilia abundance for CC+OA was not significantly different from the RT, CC, and CC+OA+RT. A cluster analysis was performed to determine how the management systems are related in terms of the relative abundance of bacterial class. From the cluster analysis graph, the management systems were classified into three groups (Figure 3.1B; marked by the green lines). The CC+OA+RT and the RT were classified into one group, CC+OA into another group, and CC and Nss into a different group. Bray-Curtis similarity (or dissimilarity) ranges from 0 to 1, where 0 indicates the groups of the management systems share a similar relative abundance of bacteria and 1 indicates complete dissimilarity.

Figure 3.2A shows a box plot of the alpha diversity of bacteria. Chao1 was used as the index for the alpha diversity of bacteria. The management systems did not significantly affect the bacterial alpha diversity ($p = 0.060$). Although no significant differences were observed between the management systems, the CC+OA+RT tended to have lower alpha diversity compared to the other management systems (14-19% lower). No distinct differences were observed between the management systems for the beta diversity of bacteria ($p = 0.219$; Figure 2B).

Sodariomycetes were the most abundant fungal class for all the management systems (Figure 3.3A). The analysis of variance (ANOVA) of the linear mixed model indicated that the management systems significantly affected the relative abundance of Sordariomycetes and Eurotiomycetes (Table S3.4, S3.6). The Nss and CC significantly had higher Sordariomycetes abundance than the RT and CC+OA+RT but not CC+OA. The RT significantly had higher Eurotiomycetes abundance than the CC+OA+RT, CC+OA, CC, and Nss. Also, the Eurotiomycetes abundance for CC+OA+RT was significantly higher than that of the CC+OA, CC, and Nss. The cluster analysis classified the management systems into two main groups based on the relative abundance of the fungal class (Figure 3.3B; marked by the green lines). The CC+OA+RT and RT were classified into one group and the CC+OA, CC, and Nss were classified into a separate group. The management systems did not significantly affect the fungi alpha diversity ($p = 0.125$). Despite the lack of significant differences between the management systems, the RT tended to have higher alpha diversity than the other systems (Figure 3.4A; 21-38% higher). The NMDS ordination plot showed no distinct differences between the management systems for the beta diversity of fungi ($p = 0.445$; Figure 3.4B).

3.3.2. Soil respiration, soil organic matter, and soil pH

The ANOVA results from the linear mixed model showed that when averaged across all the management systems, the soil respiration and organic matter changed significantly over the years (Table S3.7, S3.8). The management × time interaction effect was not significant for soil respiration, organic matter, and pH. The management systems had a significant effect on only soil respiration. In 2021, the CC+OA had 31% higher soil respiration than the Nss (Figure 3.5a). However, the soil respiration for the CC+OA was not statistically different from that of the RT, CC, and CC+OA+RT. In 2023, the soil respiration for the CC, CC+OA, and CC+OA+RT was higher than that of the RT and Nss but the differences were significant for only RT (Figure 3.5c). Soil respiration was 34% and 79% higher in CC plots compared to the Nss and RT, respectively. In the CC+OA plots, the respiration increased by 46% and 96% compared to the Nss and RT, respectively. The highest increase was observed in the CC+OA+RT plots, where respiration was 58% and 111% greater than in the Nss and RT plots, respectively. Averaged across all the management systems, the soil respiration declined over the three years (Table S3.8; Figure 3.5a, b, and c). The soil respiration values were 1.86, 1.64, and 1.49 g CO_2 kg^{-1} soil hr^{-1} in 2021, 2022, and 2023, respectively.

The management systems did not significantly impact the soil organic matter and pH in all three years (Table S3.7). Despite no significant differences, the CC, CC+OA, and CC+OA+RT tended to have more organic matter than the RT and Nss in 2023 (Figure 3.5f). The CC had 12% and 14% higher organic matter than Nss and RT, respectively. The CC+OA had 24% and 26%

higher organic matter than Nss and RT, respectively. The CC+OA+RT had 13% and 16% higher organic matter than Nss and RT, respectively. The test statistics indicated that the average organic matter for all the management systems changed over the three years (Table S3.8). The organic matter increased by 7.7 % from 2021 to 2022 but stabilized in 2023 (14.6, 15.8, and 15.6 g kg^{-1} in 2021, 2022, and 2023, respectively). No significant differences were observed between the management systems for the soil pH (Figure 3.5g, h, and i). Also, when averaged across the management systems, the soil pH was similar in all years (6.42, 6.39, and 6.36 in 2021, 2022, and 2023, respectively; Table S3.8).

3.3.3. Soil nutrients

The ANOVA of the linear mixed model indicated that the management systems had no significant effect on all the soil nutrients. However, when averaged across all the management systems, all the soil nutrients except Zn and Cu significantly changed over the years (Table S3.7, Table 3.2). The management × year interaction was significant for only P. Available N was higher in 2021 than in 2022 and 2023 (Table S3.8). An opposite trend was observed for P, K, and Fe, where the concentrations were higher in 2022 and 2023 than in 2021. The concentrations of Mg, Ca, S, and Mn were consistently higher in 2022 than in 2021 and 2023. The B concentration changed over the years, but the differences were marginal. The Zn and Cu concentrations were similar for all three years (Table S3.8). To compare the management systems based on cumulative soil nutrients, we conducted a cluster analysis of the soil nutrient data in the third year (2023). The cluster analysis classified the management systems into two main groups (Figure 3.6). The CC, CC+OA, CC+OA+RT, and Nss were classified into one group, and the RT into another group (Figure 3.6; marked by the green lines). Within the CC, CC+OA, CC+OA+RT, and Nss groups, the CC and CC+OA were sub-grouped, while the CC+OA+RT and Nss were differentiated from the CC and CC+OA.

3.4. Discussion

When averaged across all the management systems, the most abundant bacterial class was Thermoleophilia. The observed abundance of Thermoleophilia could be due to the warm temperature conditions at the location. As the name suggests, Thermoleophilia can thrive in warm temperatures (Habtewold et al., 2021; Hu et al., 2019). Tifton, GA, where the study was conducted, has a subtropical climate, which is generally warm and moist (AEMN, 2025). Comparing the Thermoleophilia abundance between the management systems, the Nss had a higher abundance than CC+OA. The Nss had less plant cover and may have had warmer soil than the CC+OA. On the contrary, Thermoleophilia are copiotrophs, microorganisms that grow well in rich organic substrates (particularly carbon) and were expected to be more abundant in the CC+OA plots than the Nss (Ho et al., 2017; Habtewold et al., 2021). This suggests that soil temperature had a greater impact on Thermoleophilia abundance than the soil organic matter.

The cluster analysis classified the CC+OA+RT and the RT into one group, CC+OA into another group, and CC and Nss into a different group. However, the differences between these groups were marginal based on the Bray-Curtis similarity/dissimilarity distance. Bray-Curtis similarity (or dissimilarity) ranges from 0 to 1, where 0 indicates the groups of the management systems share a similar relative abundance of bacteria and 1 indicates complete dissimilarity. The marginal differences in the cluster analysis and the lack of differences in the relative abundance of the other bacteria classes (Alphaproteobacteria, Actinobacteria, Bacilli, Actinobacteriota, Acidobacteriae, Planctomycetes, Gemmatimonadetes) indicate the management systems caused a minimum shift in the bacteria community at the class level. The lack of differences in key edaphic factors such as soil pH and nutrients could explain the minimal shift in the bacterial community. Studies have substantiated the direct and indirect effects of soil pH and nutrients on the soil microbial community (Zhang et al., 2017; Zhou et al., 2017; Habteselassie et al., 2022). Our results showed that intensive sustainable management practices (CC+OA+RT) tended to decrease the bacterial alpha diversity (species richness). The combination of cereal rye, animal manure, and biochar in a reduced tillage system may have led to the dominance of certain bacterial species over others.

The Nss and CC significantly had higher Sordariomycetes abundance than RT and CC+OA+RT. The Nss and CC were managed under conventional tillage, whereas the RT and CC+OA+RT were strip tilled. The RT and CC+OA+RT plots were expected to have higher Sordariomycetes abundance than the Nss and CC due to the less disturbance of the soil. For the Eurotiomycetes, the RT had higher abundance compared to the CC+OA+RT, CC+OA, CC, and Nss. Also, the CC+OA+RT had higher Eurotiomycetes abundance than the CC+OA, CC, and Nss.

The cluster analysis revealed that tillage had a dominant effect on the relative abundance of fungi with reduced tillage systems (RT and CC+OA+RT) and conventional tillage systems (Nss, CC, and CC+OA) grouped separately. Also, the observed higher fungi alpha diversity (species richness) for the reduced tillage systems could be due to the less disturbance of the fungi hyphae. The dominant fungi classes found in our study (Sodariomycetes, Dothideomycetes, and Eurotiomycetes) are all within the phylum Ascomycota, known to possess hyphae (Wang et al., 2023; Piazza et al., 2019). The unique benefits of the hyphae include the efficient absorption of nutrients and the ability to withstand extreme environmental conditions. The hyphae have a large surface area, allowing the efficient absorption of nutrients. Disrupting the hyphae, therefore, adversely affects the activities and proliferation of fungi that belong to the phylum Ascomycota (Bonfante and Genre, 2010). Studies have shown that fungi diversity was higher under conservation tillage systems compared to conventional tillage (Six et al., 2006; Simmons and Coleman, 2008).

The inclusion of cover crops only or cover crops and organic amendments resulted in high soil respiration in the third year, which is possibly due to the extra organic matter supplied to the soil microorganisms (USDA-NRCS, 2014; Franzluebbers, 2021; Gong et al., 2022). Also, the cover crop was actively growing at the time of soil sampling and may have provided a rich niche for the soil microbes (Muhammad et al., 2021). Soil respiration is an indicator of microbial activity, with higher soil respiration values indicating more microbial activity. Our results also showed that soil respiration declined over the three years, particularly when comparing 2021 to 2023. The 2022 season was under rainfed conditions, while the 2020 and 2021 seasons were irrigated, which could explain the decline in soil respiration in 2023. Dry soil condition tends to adversely impact microbial activities because it restrict the diffusion of substrates and cause the loss of microbial cell turgor, analogous to wilting in plants (Schimel, 2018).

Adding cover crops only or cover crops and organic amendments tended to increase the soil organic matter in the third year. Cereal rye and organic amendments (poultry litter and biochar) have been demonstrated to build soil organic matter (Nyakatawa et al., 2001; Bista et al., 2019; Pinnamaneni et al., 2022). Time had a profound effect on the soil organic matter, with the organic matter increasing from 2021 to 2022 and stabilizing in 2023. Soil pH did not change over the three years, indicating that none of the management systems was a major driver of soil pH in our study.

The absence of significant impacts of the management systems on all the soil nutrients suggests that the addition of organic amendments, particularly animal manure, did not enrich the soil fertility. There is a possibility that the previous crops utilized the nutrients from the animal manure, or the residual nutrients were not bioavailable at the time the soil samples were collected. Tillage had a dominant impact on the overall soil nutrients, followed by CC, as revealed by the cluster analysis. The RT and the Nss had less plant cover and may have had minimal nutrient uptake during the winter period compared to the CC plots. Studies have reported a significant uptake of nitrogen (N) by rye cover crop during the winter period (Sedghi and Weil, 2022).

3.5. Conclusions and Implications

In this study, we evaluated the impact of sustainable management systems (single, two-integrated, and three-integrated systems) on soil biological and chemical properties. The two-integrated and three-integrated systems did not significantly increase the relative abundance of Thermoleophilia, the most abundant bacterial class. Also, the three-integrated system tended to have lower bacterial alpha diversity. The combination of cereal rye, animal manure, and biochar in a reduced tillage system may have led to the dominance of certain bacterial species over others. Tillage had a dominant effect on the fungi abundance and alpha diversity. The RT tended to have higher fungi alpha diversity, but the effect was not significant. The observed higher fungi alpha diversity (species richness) for the RT could be due to the less disturbance of the fungi hyphae. On the contrary, including CC and OA in the RT did not enhance the fungi alpha diversity. In the third year, plots with CC resulted in higher soil respiration, indicating the cover crop had a dominant effect. The management systems did not significantly impact the soil organic matter, pH, and nutrients. Overall, increasing the levels of sustainable management systems did not consistently improve the soil biological and chemical properties. Moreover, the addition of biochar to the OA plots may have masked the effect of the cover crop and the poultry litter, particularly in conservation tillage systems where incorporation does not occur.

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Tables

Table 3.1: Mean temperature and total monthly precipitation in Tifton from 2020 to 2023.

Month	2020	2021	2022	2023		2020	2021	2022	2023
	Mean temperature					Total precipitation			
	-------------------- °C -------------------					-------------------- mm ----------------			
January	12.3	10.0	9.2	12.6		81	178	167	149
February	12.9	12.1	13.5	16.0		152	223	60	108
March	19.3	17.0	17.2	16.5		126	119	101	73
April	19.2	18.4	19.3	19.0		144	173	58	88
May	22.6	22.2	24.3	22.0		66	27	32	77
June	25.8	26.3	28.1	25.1		129	204	99	186
July	28.1	26.9	27.6	27.4		47	207	142	132
August	27.9	27.2	27.0	27.9		116	149	207	160
September	24.5	24.7	23.9	24.1		133	90	63	61
October	22.2	20.4	17.9	18.7		63	94	26	33
November	17.3	13.1	15.3	14.6		61	13	87	19
December	10.3	16.4	11.5	11.2		121	71	37	177
Average	20.2	19.6	19.6	19.6	Total	1238	1547	1079	1262

Table 3.2: Impacts of management systems on soil nutrients in 2021, 2022, and 2023.

Management system	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
						mg kg^{-1}					
						2021					
Nss	6.40±1.10a	116±8a	82.6±4.6a	29.6±1.9a	380±46a	6.12±0.60a	0.43±0.03a	4.13±0.70a	34.5±2.3a	90±8a	8.95±1.00a
RT	6.79±0.37a	114±12a	69.7±4.0a	37.8±4.2a	413±45a	7.37±0.59a	0.43±0.02a	3.90±0.66a	35.9±4.5a	93±5a	7.73±1.11a
CC	8.08±1.73a	97±17a	61.6±5.0a	27.1±3.5a	379±73a	7.32±0.42a	0.43±0.02a	3.91±0.59a	52.4±6.1a	97±7a	8.31±1.01a
CC+OA	8.16±1.18a	102±12a	61.9±9.5a	29.8±2.4a	363±44a	6.59±0.96a	0.45±0.03a	4.48±0.68a	45.0±3.7a	101±8a	7.94±1.28a
CC+OA+RT	8.91±1.91a	120±18a	78.1±16.5a	36.3±4.5a	356±30a	6.66±0.62a	0.44±0.03a	4.78±1.30a	44.2±5.5a	99±13a	9.19±1.43a
						2022					
Nss	5.48±0.22a	136±8a	94.8±6.9a	43.4±4.2a	544±42a	7.85±0.87a	0.33±0.01a	3.79±0.22a	53.8±2.7a	112±7a	8.71±0.91a
RT	6.00±0.77a	120±14a	117.8±5.5a	43.7±1.5a	530±25a	9.89±0.90a	0.38±0.08a	2.87±0.81a	50.0±1.7a	108±5a	7.54±0.79a
CC	5.18±0.60a	111±18a	83.2±16.0a	47.0±6.3a	592±48a	10.45±1.48a	0.32±0.03a	3.66±0.39a	59.5±3.7a	112±12a	8.25±1.02a
CC+OA	5.85±1.05a	130±12a	84.9±4.9a	56.8±1.5a	647±24a	11.16±1.50a	0.39±0.03a	3.62±1.02a	59.5±2.5a	117±8a	8.30±1.09a
CC+OA+RT	5.38±1.20a	156±2a	102.6±12.6a	56.0±4.6a	586±24a	10.80±0.92a	0.47±0.13a	3.00±0.78a	59.2±1.4a	123±7a	8.80±0.59a
						2023					
Nss	0.90±0.13a	140±17a	112.6±8.6a	29.5±2.9a	383±37a	7.58±0.59a	0.40±0.04a	3.64±0.32a	33.6±1.8a	112±9a	8.18±0.65a
RT	0.56±0.31a	116±12a	109.3±11.2a	35.0±7.4a	395±76a	7.86±2.28a	0.40±0.06a	3.47±0.57a	34.4±4.2a	114±12a	8.15±0.60a
CC	1.00±0.12a	124±21a	99.9±10.0a	37.4±9.2a	421±66a	9.34±1.02a	0.43±0.04a	3.50±0.55a	40.7±2.0a	109±5a	7.70±0.89a
CC+OA	1.30±0.28a	142±9a	104.7±11.8a	42.8±5.4a	459±46a	8.68±1.13a	0.43±0.01a	4.35±0.85a	37.8±1.9a	109±10a	7.58±0.77a
CC+OA+RT	1.49±0.59a	120±10a	102.1±9.2a	35.3±5.4a	398±51a	7.79±1.15a	0.40±0.03a	3.83±0.90a	34.4±1.5a	103±6a	8.08±0.99a

Within each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error (n = 4). Nss, no sustainable system; RT, reduced tillage; CC, cover crop; CC+OA, cover crop + organic amendments; CC+OA+RT, cover crop + organic amendments + reduced tillage. N: NO_3-N and NH_4-N.

Figures

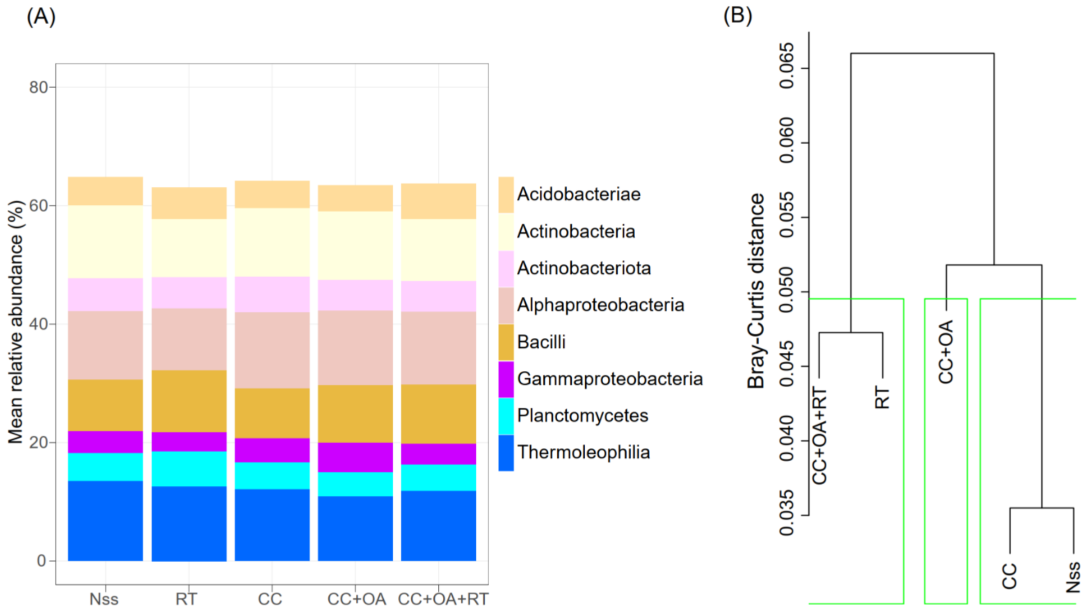

Figure 3.1: Stacked bar graph (A) and cluster analysis graph (B) of bacterial relative abundance at the class level. Class-level assessment helps group bacteria by their ecological and functional roles. The graph represents the mean relative abundance of bacterial class with at least 5% relative abundance for any of the management systems. Nss, no sustainable system; RT, reduced tillage; CC, cover crop; CC+OA, cover crop + organic amendments; CC+OA+RT, cover crop + organic amendments + reduced tillage.

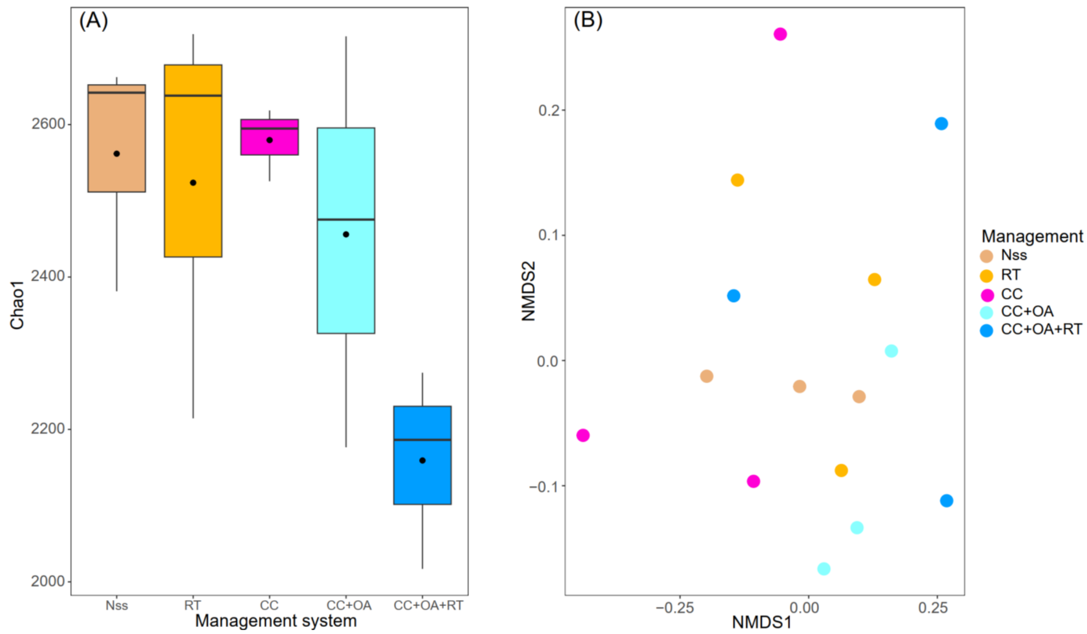

Figure 3.2: Alpha diversity of bacteria (A) and beta diversity of bacteria (B) for all the management systems in the third year. Chao1 was used as the index for alpha diversity (species richness). Beta diversity measures the diversity of the bacteria species between the management systems. Black points in the box plots (A) represent the mean and the lower black vertical line, black horizontal line, and upper black vertical line are the lower quartile, median, and upper quartile, respectively. Nss, no sustainable system; RT, reduced tillage; CC, cover crop; CC+OA, cover crop + organic amendments; CC+OA+RT, cover crop + organic amendments + reduced tillage.

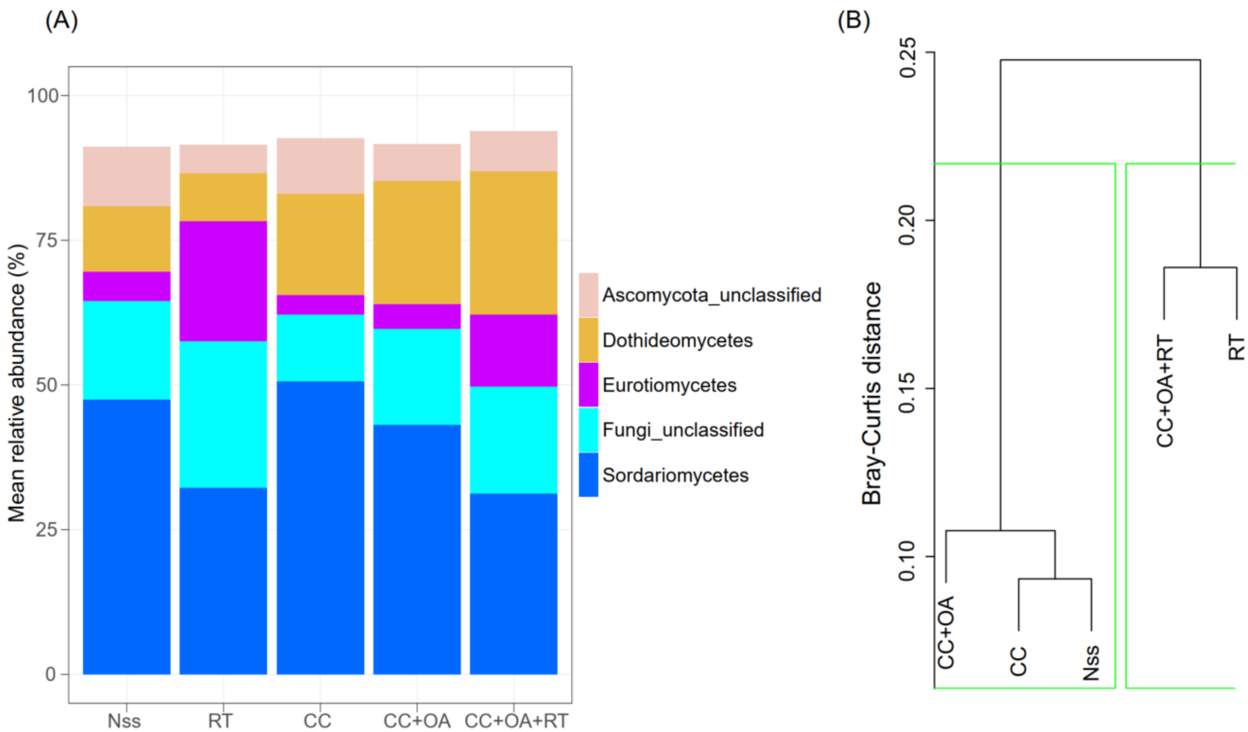

Figure 3.3: Stacked bar graph (A) and cluster analysis graph (B) of fungi relative abundance at the class level. Class-level assessment helps group fungi by their ecological and functional roles. The graph represents the fungi class with a mean fungi relative abundance of at least 5% for any of the management systems. Nss: no sustainable system; RT: reduced tillage; CC: cover crop; CC+OA: cover crop + organic amendments; CC+OA+RT: cover crop + organic amendments + reduced tillage.

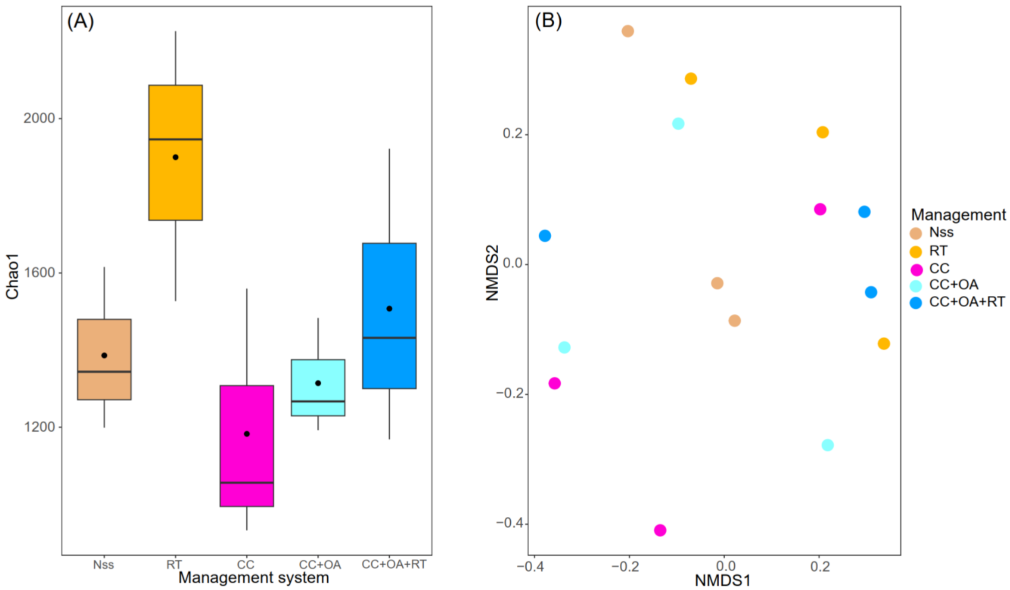

Figure 3.4: Alpha diversity of fungi (A) and beta diversity of fungi (B) for all the management systems in the third year. Chao1 was used as the index for alpha diversity (species richness). Beta diversity measures the diversity of the fungi species between the management systems. Black points in the box plots (A) represent the mean and the lower black vertical line, black horizontal line, and upper black vertical line are the lower quartile, median, and upper quartile respectively. Nss, no sustainable system; RT, reduced tillage; CC, cover crop; CC+OA, cover crop + organic amendments; CC+OA+RT, cover crop + organic amendments + reduced tillage.

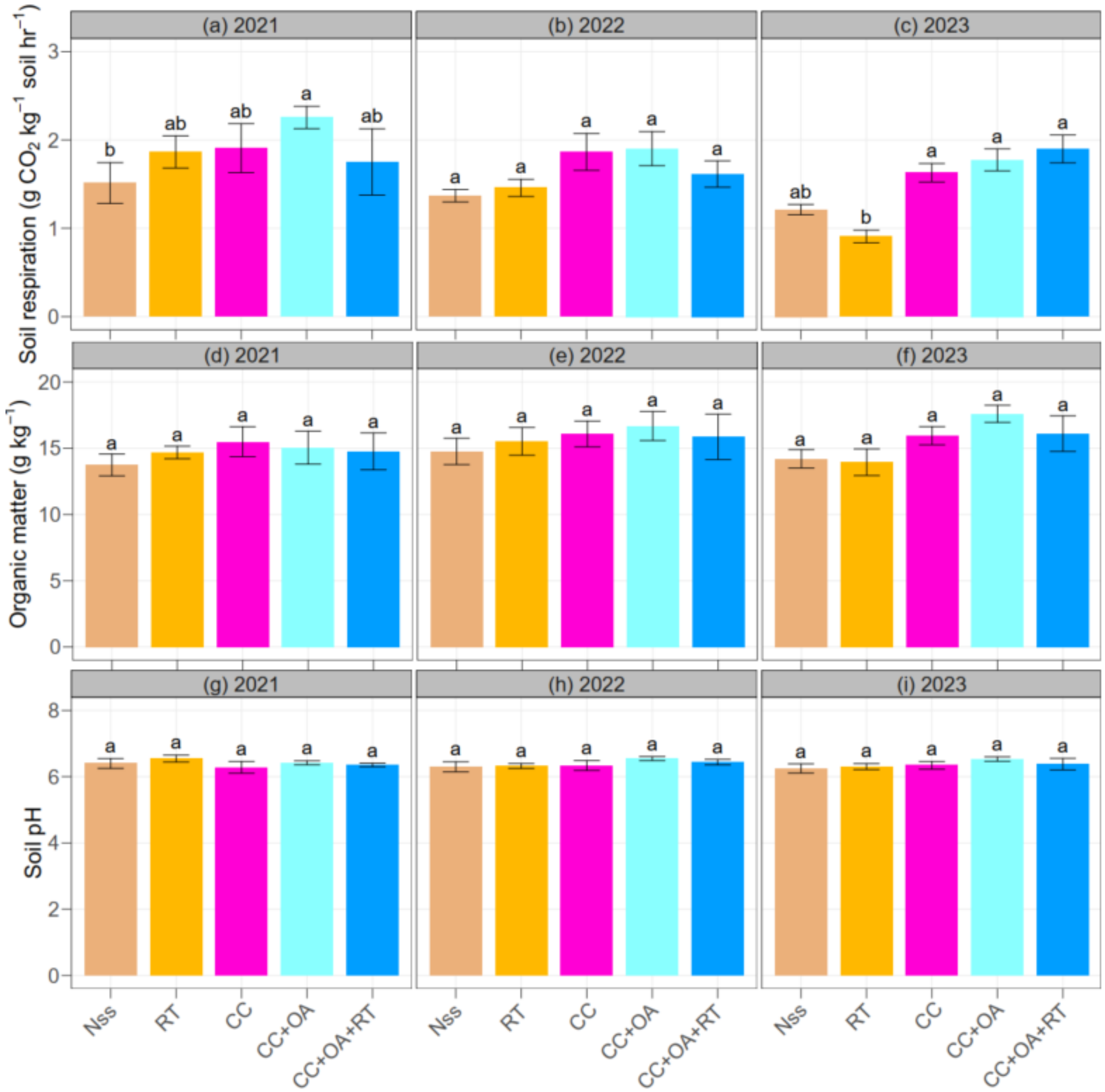

Figure 3.5: Impacts of management systems on soil respiration, organic matter, and pH in 2021, 2022, and 2023. Within each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Error bars represent standard errors of the mean (n = 4). Nss, no sustainable system; RT, reduced tillage; CC, cover crop; CC+OA, cover crop + organic amendments; CC+OA+RT, cover crop + organic amendments + reduced tillage.

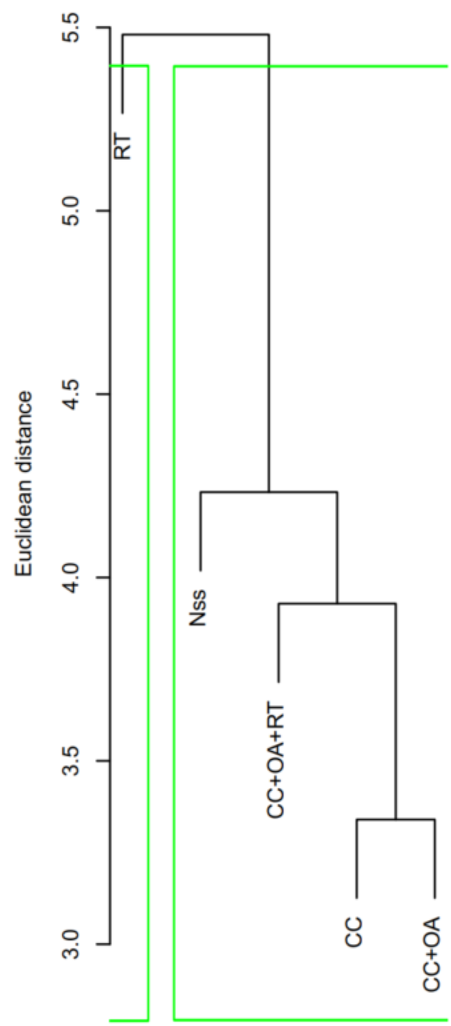

Figure 3.6: Cluster analysis graph of 2023 soil nutrients. Nutrient data were scaled and aggregated. Nss, no sustainable system; RT, reduced tillage; CC, cover crop; CC+OA, cover crop + organic amendments; CC+OA+RT, cover crop + organic amendments + reduced tillage.

Supplemental Tables

Table S3.1: Nutrient composition of organic amendments used in the study.

Organic amendment	Total C	Total N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
	---------- $g\ kg^{-1}$ ----------											
	---------- 2020 ----------											
Cattle manure	83.8	10.1	9.84	5.85	3.51	13.1	1.78	0.02	0.8	0.25	23.1	1.05
Biochar	458	3.88	0.7	6.09	0.38	0.75	0.22	0.01	0.02	0.01	0.43	0.06
	---------- 2021 ----------											
Broiler litter	275	39.8	16.5	40.1	9.18	3.52	15.8	0.12	0.37	0.37	4.28	0.49
Biochar	866	2.95	1.77	4.88	3.45	24	0.37	0.25	0.25	0.49	0.86	0.25
	---------- 2022 ----------											
Broiler litter	275	39.1	16.8	39.9	9.2	34.8	15.8	0.12	0.55	0.37	4.46	0.49
Biochar	866	2.95	1.77	4.88	3.45	24	0.37	0.25	0.25	0.49	0.86	0.25

Corn cobs and stalks were the feedstock of the biochar used in 2020, and pine wood waste was the feedstock of the biochar used in 2021 and 2022.

Table S3.2: Organic amendment application and soil sampling dates

Field activity	2020	2021	2022	2023
Soil sampling	NA	Mar. 22, 2021	Apr. 12, 2022	April 17, 2023
Biochar	May 18 and Nov. 19, 2020	Nov. 26, 2021	NA	NA
Animal manure	May 18, 2020	May 6, 2021	May 3, 2022	NA

Animal manure; cattle manure in 2020, and broiler litter in 2021 and 2022.

Table S3.3: Rates of inorganic nutrients applied.

Year	N	P_2O_5	K_2O	S	B
	-------------------- kg ha^{-1} --------------------				
2020	84.1	89.7	78.5	11.2	0.56
2021	-	-	-	-	-
2022	50.4	89.7	112.1	11.2	0.56

Urea ammonium nitrate solution, diammonium phosphate, potassium chloride, potassium sulfate, and Borosol® 10 solution were used as fertilizer sources. In 2021, no inorganic fertilizer was applied because the soil test indicated the nutrients were sufficient for growing peanuts.

Table S3.4: The *p*-values of the effects of the management systems on bacteria and fungi relative abundance at the class level in 2023.

Management Effects	*p*-values
Bacteria (class level)	
Thermoleophilia	**0.033**
Planctomycetes	0.117
Gammaproteobacteria	0.083
Bacilli	0.772
Alphaproteobacteria	0.088
Actinobacteria	0.241
Actinobacteriota	0.541
Acidobacteriae	0.668
Fungi (class level)	
Sordariomycetes	**0.001**
Fungi_unclassified	0.291
Eurotiomycetes	**<0.001**
Dothideomycetes	0.161
Ascomycota_unclassified	0.117

Note: Bold texts indicate significant effect terms ($p < 0.05$)

Table S3.5: The effects of management systems on bacteria relative abundance at the class level in 2023.

Management system	Thermoleophilia	Planctomycetes	Gammaproteobacteria	Bacilli	Alphaproteobacteria	Actinobacteriota	Actinobacteria	Acidobacteriae
				%				
Nss	13.5±0.8a	4.65±0.23a	3.74±0.16a	8.7±0.8a	11.6±0.2a	5.55±0.17a	12.3±0.5a	4.74±0.58a
RT	12.6±0.1ab	5.90±0.28a	3.26±0.28a	10.4±0.2a	10.5±0.2a	5.23±0.80a	9.9±0.6a	5.29±0.40a
CC	12.2±0.9ab	4.52±0.65a	4.03±0.41a	8.4±0.3a	12.8±0.5a	6.00±0.10a	11.7±0.6a	4.54±0.83a
CC+OA	11.0±0.7b	3.99±0.10a	5.01±0.70a	9.7±0.7a	12.6±0.7a	5.11±0.19a	11.6±0.5a	4.39±0.23a
CC+OA+RT	11.9±0.6ab	4.38±0.66a	3.50±0.78a	10.0±2.6a	12.4±1.1a	5.12±0.79a	10.4±1.7a	6.01±1.62a

The table represents a mean relative abundance of at least 5 % for any of the management systems. Means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Values represent the mean ± standard error. Nss, no sustainable system; RT, reduced tillage; CC, cover crop; CC+OA, cover crop + organic amendments; CC+OA+RT, cover crop + organic amendments + reduced tillage.

Table S3.6: The effects of management systems on fungi relative abundance at the class level in 2023.

Management system	Sordariomycetes	Fungi_unclassified	Eurotiomycetes	Dothideomycetes	Ascomycota_unclassified
			%		
Nss	47.5±4.7a	17.0±3.0a	5.0±0.4c	11.3±2.3a	10.3±2.3a
RT	32.3±1.7b	25.2±4.3a	20.6±1.8a	8.5±3.5a	4.8±0.6a
CC	50.6±2.2a	11.6±1.5a	3.3±0.9c	17.5±4.6a	9.5±0.9a
CC+OA	43.1±2.1ab	16.6±3.4a	4.2±1.0c	21.3±4.8a	6.5±1.4a
CC+OA+RT	31.3±0.8b	18.4±6.2a	12.4±0.5b	24.9±7.8a	6.8±1.2a

The table represents a mean relative abundance of at least 5 % for any of the management systems. Means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Values represent the mean ± standard error. Nss, no sustainable system; RT, reduced tillage; CC, cover crop; CC+OA, cover crop + organic amendments; CC+OA+RT, cover crop + organic amendments + reduced tillage.

Table S3.7: *p*-values of the main effects and interaction effects of management systems and year on soil properties.

Effects	Respiration	Organic matter	Soil pH	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
Management (M)	**0.008**	0.521	0.717	0.387	0.690	0.431	0.414	0.904	0.437	0.631	0.888	0.054	0.990	0.942
Year (Y)	**0.003**	**0.008**	0.503	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.035**	0.136	**<0.001**	**<0.001**	0.076
M x Y	0.091	0.273	0.378	0.480	**0.027**	0.329	0.228	0.216	0.867	0.845	0.969	0.214	0.228	0.431

Note: Bold texts indicate significant effect terms ($p < 0.05$). N: NO_3-N and NH_4-N.

Table S3.8: The effects of all the management systems over time on soil properties.

Year	Respiration	Organic matter	Soil pH	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
	g CO_2 kg^{-1} soil hr^{-1}	g kg^{-1}		---------- mg kg^{-1} ----------										
2021	1.86a	14.6b	6.42a	7.67a	110b	70.8b	32.1b	378b	6.81b	0.44a	4.24a	42.4b	96b	8.42a
2022	1.64ab	15.8a	6.39a	5.58b	131a	96.7a	49.4a	580a	10.03a	0.38b	3.39a	56.4a	114a	8.32a
2023	1.49b	15.6a	6.36a	1.05c	128a	105.7a	36.0b	411b	8.25b	0.41ab	3.76a	36.2c	110a	7.94a

Means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). N: NO_3-N and NH_4-N.

Supplemental Figures

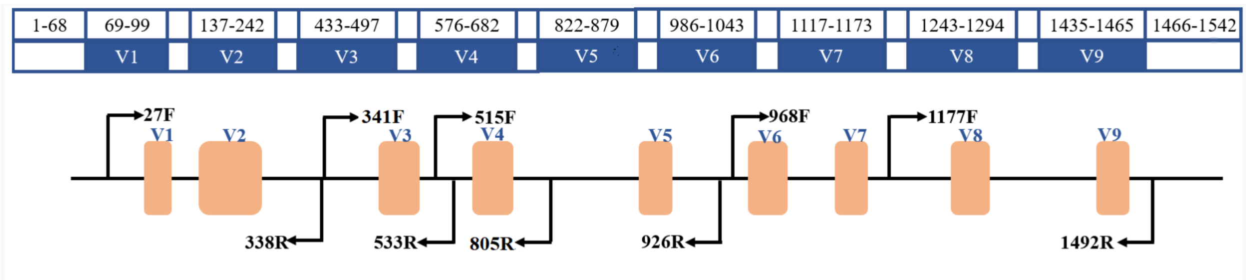

Figure S3.1: 16S rDNA region of bacteria (LC Sciences, 2023). In prokaryotes, the 16S rDNA sequence (1,542 bp) is the coding region of the 16S rRNA transcript. This comprises 9 variable regions (V1 to V9) and 10 conserved regions (highlighted in white). The variable region is highly diverse among species and can be used for taxonomic classification.

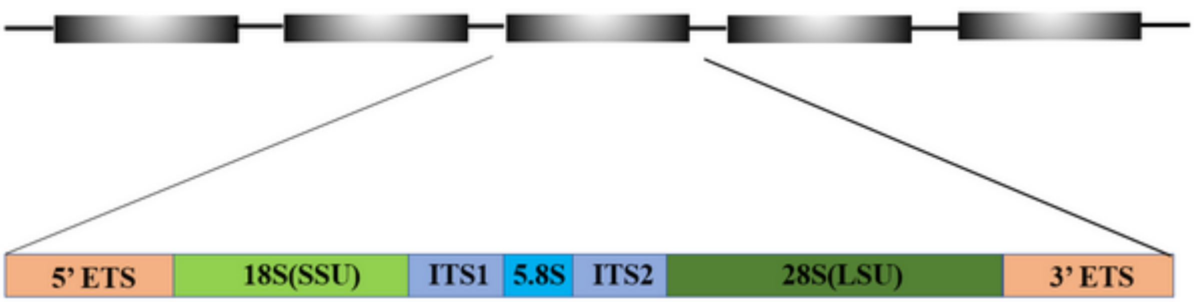

Figure S3.2: Internal transcribed spacer (ITS) region of fungi (LC Sciences, 2023). The ITS1 and ITS2 regions are moderately conserved compared to the 5.8s, 18S, and 28S rRNA, making ITS suitable for molecular identification of fungi.

CHAPTER 4

REGENERATIVE AGRICULTURAL PRACTICES IN ROW CROP PRODUCTION: IMPACTS ON PRODUCTIVITY, QUALITY, AND NUTRIENT UPTAKE

Ankomah, G., Habteselassie, M. Y., Black, A. R., Brown, N., & Sintim, H. Y. (2025). Regenerative agricultural practices in row crop production: impacts on productivity, quality, and nutrient uptake.

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Abstract

Poor soil health conditions pose a challenge to the sustainable production of row crops in Georgia, USA. Regenerative agricultural practices can be employed to improve soil health and row crop productivity. A three-year study was established at the Southeast Georgia Research and Education Center, Midville, GA, to evaluate the impacts of regenerative agricultural practices on row crop productivity, quality, and nutrient uptake. The management systems included conventional tillage (CT; control), reduced tillage (RT), reduced tillage with cereal rye (*Secale cereale;* RT+CR), reduced tillage with cereal rye and poultry (broiler) litter (RT+CR+PL), reduced tillage with cereal rye, poultry litter, and biochar (RT+CR+PL+BC). The CR was planted at a rate of 56 kg ha^{-1} in the fall of each year and terminated in the spring. The PL rate applied in the RT+CR+PL plots was 4.48 Mg ha$^{-1.}$ The RT+CR+PL+BC received 2.24 Mg ha^{-1} each of PL and BC. The row crops evaluated were corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and peanut (Arachis hypogaea L.). The management systems had a minimal impact on the row crop productivity and quality. The RT+CR+PL and RT+CR+PL+BC increased cottonseed yield in 2021 and peanut biomass in 2022, but the differences were not always significant compared to the other management systems. The RT performed similarly to the CT in terms of crop yields, indicating that the strip tillage was effective in seedbed preparation. Differences in nutrient uptake in crop biomass, particularly corn and peanut, did not translate into an increase in crop yields.

4.1. Introduction

Cotton (*Gossypium hirsutum* L.), peanut (Arachis hypogaea L.), and corn (*Zea mays* L.) contribute immensely to the agricultural economy of the state of Georgia and the broader USA. The 2024 Ag Snapshots report on Georgia's agricultural economy highlights that these three row crops ranked among the top ten commodities in the state by value, contributing a total of $2.6 billion annually. In terms of production value, cotton is ranked first, followed by peanut, and then corn. Cotton, peanut, and corn production account for 39.6%, 23.9%, and 15.8%, respectively, of all row and forage crops (Kane, 2024). In addition, these row crops provide essential raw materials for food, fiber, and industrial products (Khan et al., 2020; Machado et al., 2025; USDA-ERS, 2025). Corn and peanut are important sources of food for humans and feed for livestock. Corn is a key source of feed for the livestock industry, particularly the poultry industry, due to its large-scale production (Kane, 2024).

Degraded soil health conditions are a major constraint to the sustainable production of these row crops. Coastal Plain soils of Georgia are predominantly Ultisols, which have a sandy topsoil layer underlaid by a kaolinitic subsoil. The soils have low organic matter and are depleted of essential plant nutrients as a result of adverse weather conditions and intensive cultivation (Ankomah et al., 2024; Amissah, Ankomah, Lee, Sohag et al., 2024; Truman et al., 2010; MacHmuller et al., 2015). Low levels of soil organic matter and nutrients have been identified as key factors that affect crop productivity (Oldfield et al., 2019; Lal, 2020; Havlin, 2020).

Management practices that can improve soil health and ensure sustainable crop production are crucial.

Conservation tillage, cover crops (CC), and organic amendments have been widely recognized as regenerative agricultural practices that conserve soil and water resources (USDA-NRCS, 2024). Regenerative agricultural practices align with the soil health principles established by the USDA-NRCS, which are minimizing soil disturbance, maximizing soil cover, maintaining living roots, and maximizing biodiversity (USDA-NRCS, 2024). Regenerative agricultural practices have been demonstrated to provide numerous soil functions and ecosystem services (Adeli et al., 2024; Busari et al., 2015; Mitchell et al., 2017). Studies have demonstrated that these practices improve soil health by increasing soil organic matter and nutrient cycling potential (Adeli et al., 2019; Ankomah et al., 2024; Franzluebbers, 2021; Farmaha et al., 2022). Conservation tillage and cover crops have been identified to have increased soil carbon by 19% (Adeli et al., 2024). In a previous study, Adeli et al. (2019) found that in the presence of CC residue, PL increased soil carbon by 22%.

Improvement in soil health has been associated with increased crop productivity (Adeli et al., 2019, 2024; Lal, 2020; Oldfield et al., 2019). Adeli et al. (2019) observed a 12% increase in cotton lint yield with the application of poultry litter. In a different study, Adeli et al. (2022) observed a 42% increase in cotton lint yield when poultry litter was applied together with biochar and inorganic fertilizer. In a recent study, the application of poultry litter was reported to have increased corn grain yield (Adeli et al., 2024). A review paper by Lin et al. (2018) indicated that

PL increased corn, cotton, and peanut yields. Another study revealed that the application of biochar with poultry manure increased corn yield, which correlated positively with soil organic carbon, available N, and P (Arif et al., 2017).

Despite the benefits obtained from implementing these regenerative agricultural practices, there are unique challenges associated with individual practice (Ankomah et al., 2024). For instance, cereal rye under a conservation tillage system has been previously reported to decline corn yield. The decline in corn yield was attributed to reduced N uptake as a result of microbial immobilization (Preza-Fontes et al., 2022). Also, biochar is a stable carbon source that can build soil carbon, but the high C/N ratio could lead to N immobilization (Abban-Baidoo et al., 2024; Agegnehu et al., 2015). Integrating cereal rye, poultry litter, and biochar in a reduced tillage system could improve crop productivity. Additionally, poultry litter is a rich source of nutrients (Ankomah et al., 2024; Chastain et al., 2010), which can enhance the nutritional content of corn, peanut, and cotton seeds, as well as nutrient uptake in the residual biomass, when incorporated into a reduced tillage and cereal rye system. The seeds as well as the by-products are significant sources of food and feed for humans and livestock, respectively (Machado et al., 2025; USDA-ERS, 2025; Zia et al., 2022). Therefore, enhancing the nutrient content of the seeds could potentially improve the nutritional status of humans and livestock (Arya et al., 2016; Huang et al., 2020). The objective of the study was to evaluate the impacts of reduced tillage, cereal rye, poultry litter, and biochar on row crop productivity, quality, and nutrient uptake.

4.2. Materials and Methods

4.2.1. Experimental site

Field studies were conducted from 2021 to 2023 at the Southeast Georgia Research and Education Center, Midville, GA (32°52'46.44" N, 82°12'33.86" W). The soil at the study site is a Dothan sandy loam, classified as Fine-loamy, kaolinitic, thermic Plinthic Kandiudults. The sand, silt, and clay content of the soil (0-15 cm depth) were 93.3%, 0.20%, and 6.5%, respectively. The long-term (1958 to 2016) average air temperature and precipitation were 18 °C and 1147 mm, respectively (AEMN, 2025).

4.2.2. Experimental design and plot management

Field studies were established to evaluate the impacts of regenerative agricultural practices on row crop productivity, quality, and nutrient uptake. The management systems were conventional tillage (CT; control), reduced tillage (RT), reduced tillage with cereal rye (RT+CR), reduced tillage with cereal rye and poultry (broiler) litter (RT+CR+PL), and reduced tillage with cereal rye, poultry litter, and biochar (RT+CR+PL+BC). The management systems were arranged in a randomized complete block design with four replications and a plot size of 7.3 m by 9.1 m. Cereal rye was planted in the fall with a John Deere 750 no-till drill at a seeding rate of 56 kg ha^{-1} and terminated in the spring with glyphosate [isopropylamine salt of N-(phosphonomethyl) glycine].

Tillage operations were done in the spring of each year before planting cotton, peanut, and corn. The CT plots were prepared by tilling the soil to a depth of 41 cm with a KMC tillovator (Kelly Manufacturing Co., South Dillon, SC). For the RT plots (RT, RT+CR, RT+CR+PL, RT+CR+PL+BC), only the plant rows were tilled using a KMC strip-till implement (Kelly Manufacturing Co., South Dillon, SC). The poultry litter was acquired from Powell Poultry Farms, LLC in Omega, GA, and it was applied in the RT+CR+PL plots at a rate of 4.48 Mg ha^{-1}. The RT+CR+PL+BC plots received 2.24 Mg ha^{-1} each of poultry litter and biochar. The biochar was made from pinewood waste, and it was obtained from Wakefield BioChar based in Valdosta, GA. The nutrient composition of the poultry litter and biochar is shown in Table S4.1. The key field operation dates are presented in Table S4.2.

The field was divided into three sections to enable annual evaluation of the impacts of the management systems on all three row crops. In the first section, corn, peanut, and cotton were planted in 2021, 2022, and 2023, respectively. In the second section, peanut was planted in 2021, followed by cotton in 2022 and corn in 2023. In the third section, cotton, corn, and peanut were planted in 2021, 2022, and 2023, respectively. Each year, corn was planted in April while cotton and peanut were planted in May. In 2021 and 2022, the corn variety planted was Agri Gold 6659 with a seeding rate of 84,016 and 79,074 seeds $ha^{-1,}$ respectively. In 2023, the corn variety planted was Croplan® Genetics 5678, planted at a seeding rate of 79,074 seeds ha^{-1}. For cotton, the variety planted in 2021 was Deltapine® DP 1646 B2XF at a seeding rate of 107,639 seeds ha^{-1}. The cotton variety planted in 2022 was Stoneville® ST 4550, with the same seeding rate of 107,639 seeds ha^{-}

^{1}. In 2023, Stoneville® cotton variety ST 5091 was planted at a seeding rate of 88,958 seeds ha^{-1}. Peanut variety Georgia-06G was planted in all years with seeding rates of 214,982 seeds ha^{-1} in 2021 and 2022, and 244,634 seeds ha^{-1} in 2023. There were eight rows of plants per plot with 0.9 m spacing for all three crops.

In 2021 and 2022, all plots in the corn and cotton phase received the same inorganic fertilizer. In 2023, CT, RT, and RT+CR received the full rate of the inorganic fertilizer. The RT+CR+PL and RT+CR+PL+BC received partial inorganic fertilizer after accounting for the nutrients in the poultry litter. It was estimated that 60% of the N, 80% of P, K, and S in poultry litter would be available (Bryant et al., 2020). The inorganic fertilizer sources and rates applied for corn and cotton are presented in Tables S4.3 and S4.4. The plots were fertilized according to the University of Georgia Agricultural and Environmental Services Laboratories (UGA-AESL) recommendations to achieve 1.68 Mg ha^{-1} of cotton lint yield and 15.7 Mg ha^{-1} of corn yield. In the corn study, the full rates of P, K, and S were applied at pre-planting in 2021 and 2022 and at the V3 stage (three-leaf collar) in 2023. For cotton, all of P, K, S, and B were applied at the pre-plant or early vegetative stage. The N was split-applied in both the corn and cotton studies in all years. In the corn study, N was applied at the pre-plant, V3-V4, and V6 stages (Table S4.3). In the cotton study, N was applied at the pre-plant/early vegetative stage and the square stages (Table S4.4). No inorganic fertilizers were applied for the peanut phase in all years. Weed and insect pest, and disease control followed recommendations in the production guide for the row crops developed by the University of Georgia Cooperative Extension (Bryant et al., 2020; Hand et al., 2021; Monfort et al., 2022).

4.2.4. Data collection

4.2.4.1. Initial soil analyses

Initial soil samples were collected at the block level from the 0-15 cm and 15-30 cm soil depths in fall 2020 before establishing the study. The soil samples were air-dried and ground to pass through a 2-mm sieve for chemical and nutrient analyses. Organic matter was measured using the loss on ignition method, while soil pH was determined with a pH meter (PC 9500, Apera Instruments) in a 1:2 ratio of soil to water (Crouse et al., 2014). Available soil nutrients such as phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), boron (B), zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu) were quantified following the Mehlich-I extraction procedure (Crouse et al. 2014) and using an inductively coupled plasma optical emission spectrophotometer (PerkinElmer® Avio 200 Cross-Flow ICP-OES). Nitrate-nitrogen (NO_3-N) was analyzed using a Genesys 150 UV-visible spectrophotometer (Thermo Fisher Scientific Inc.) after extraction with a 2 M KCl solution. The initial soil properties are presented in Table 4.1.

4.2.4.2. Biomass sampling and yield

The aboveground biomass of cotton was collected within a 1-m-long strip from every plot at the boll opening stage. The lint + seeds were separated from the aboveground biomass (residual biomass). Peanut plants (pods and aboveground biomass) were collected from a 0.5-m strip in 2021 and a 1-m strip in 2022 and 2023 at physiological maturity. The aboveground biomass (residual biomass) was separated from the pods. Corn plants were sampled from a uniform 1-m strip at the R6 stage and were separated into the seed and residual biomass (all other parts, excluding the seeds). All plant samples were oven-dried at 78 *°C* until constant weight. The residual biomass weights for cotton, peanut, and corn were used to calculate biomass accumulation.

Cotton was harvested with a cotton picker by sampling seed cotton (lint + seeds) from the two middle rows of every plot. The seed cotton samples were sent to the University of Georgia Micro Gin in Tifton, GA, for ginning. The gin turnout was determined by dividing the lint by the seed cotton, which was used to calculate the lint and cottonseed yields. Peanut pods (hull + seed) were harvested from the two middle rows, and the yield was determined at 105 g kg^{-1} moisture content. Corn was harvested at physiological maturity from the two middle rows of every plot with a plot combine harvester to obtain the seed weight and moisture content. The grain yield was determined at 155 g kg^{-1} moisture content.

4.2.4.3. Crop quality and nutrient uptake

Cotton lint samples were shipped to the USDA classing office in Macon, GA, to measure fiber quality parameters such as fiber length, fiber strength, micronaire, uniformity, reflectance (Rd), and yellowness (+b) following standard protocols (Cotton 2018). Peanut kernels (seeds) were graded following standard procedures (USDA 2019). The grading parameters determined were sound mature kernels (SMK), sound split (SS), total sound mature kernels (TSMK), and other kernels (OK). Peanut seeds and hulls (2021 and 2022) and corn seeds (2021, 2022, and 2023) were ground, and the total N content was measured with a 2400 Series II CHNS/O Elemental Analyzer (PerkinElmer U.S. LLC, Shelton, CT, USA). Also, total P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, and Mo were measured with Avio 200 ICP-OES (PerkinElmer U.S. LLC, Shelton, CT, USA) after sample digestion in nitric acid and hydrogen peroxide mixture using DigiPREP MS (SCP Science, Quebec, Canada). The total N was converted to protein by multiplying by a conversion factor of 6.25 (Krul, 2019).

The total C and total N in the cotton, corn, and peanut residual biomass were measured with a 2400 Series II CHNS/O Elemental Analyzer (PerkinElmer U.S. LLC, Shelton, CT, USA). Also, the other nutrients (total P, K, Ca, Mg, S, Fe, Mn, Zn, B, Cu, and Mo) were measured following the procedures as previously described. The nutrient uptake was determined by multiplying the concentrations by the residual biomass weights.

4.2.5. Data analysis

All data were analyzed with a linear mixed model using the 'lme4' package in R (Bates et al., 2015). The management systems were considered as fixed effects, and the block was a random effect. The data were analyzed separately for each year. Homoscedasticity of variance and normality of residual assumptions were tested, and appropriate transformations were performed as needed. The means were separated using the least square means and Sidak comparison procedure with the 'emmeans' package in R software (Lenth et al., 2025). The significance level of all analyses was assessed at $p = 0.05$.

4.3. Results and Discussion

4.3.1. Weather conditions

Figure 4.1 shows the monthly average temperature (top) and the monthly total precipitation in Midville, GA, from 2021 to 2023 (a, b, c). The annual average temperature was 18.5 °C, 18.8 °C, and 19.1 °C in 2021, 2022, and 2023, respectively. The annual precipitation was 1110 mm, 1003 mm, and 1354 mm in 2021, 2022, and 2023, respectively. The precipitation recorded from the planting and harvest of the crops was highest in 2023. The precipitation received between the planting and harvest of corn was 549 mm in 2021, 464 mm in 2022, and 609 mm in 2023. Also, the precipitation received between the planting and harvest of cotton was 501 mm, 470 mm, and 640 mm in 2021, 2022, and 2023, respectively. Likewise, the precipitation received between the planting and harvest of peanut was 501 mm, 509 mm, and 616 mm in 2021, 2022, and 2023, respectively.

4.3.2. Biomass and yield

4.3.2.1. Cotton biomass and yield

The management systems had no significant effect on cotton biomass and lint yield. Despite the lack of significant differences, applying PL in RT and CR (RT+CR+PL) tended to result in higher biomass accumulation compared to the other management systems in 2021 (Figure 4.2a). The cottonseed yield was significantly affected by the management systems (Table S4.5). In 2021, the cottonseed yield for the plots that received PL (RT+CR+PL and RT+CR+PL+BC) was higher than the CT, RT, and RT+CR, with a significant difference observed when compared to the CT (Figure 4.2g). The RT+CR+PL had 24%, 12%, and 18% cottonseed yield higher than the CT, RT, and RT+CR, respectively, while that of the RT+CR+PL+BC was 22%, 10%, and 16% higher than the CT, RT, and RT+CR, respectively (Figure 4.2g). A similar trend was observed for the cotton lint yield in 2021, but the differences were not significant (Figure 4.1d). Despite the lack of differences, in 2022 and 2023, the cottonseed yield for the RT+CR+PL was slightly higher than the other management systems (13-18% in 2022 and 4-15% in 2023; Figure 4.2h, i). Similarly, in 2022, the cotton lint yield for RT+CR+PL was relatively higher compared to the other management systems. In 2023, the RT+CR+PL plots received no inorganic fertilizer but had similar cotton lint yield as the CT and RT plots, which received the full rates of the inorganic fertilizer. Also, the RT+CR received the full rates of the inorganic fertilizer, but the RT+CR+PL tended to have a higher cotton lint yield in 2023 (13% higher). On the contrary, including biochar (RT+CR+PL+BC) caused a 10% and 11% decline in the cotton lint yield in 2022 and 2023, respectively, and a 13% and 10% reduction in cottonseed yield in 2022 and 2023, respectively, compared to the RT+CR+PL. The differences were, however, not statistically significant. Additionally, the RT plots performed similarly to the CT in terms of the cotton lint yield and cottonseed yield in all years (Figure 4.2d, e, f, g, h, i).

The nutrients supplied by the PL in the RT+CR+PL potentially increased cotton lint and cottonseed yields, particularly in 2023, as there was no inorganic fertilizer applied. Continuous application of PL for three years may have enriched the soil nutrients, resulting in increased cotton yields (Mitchell and Tu, 2006). Other studies have reported an increase in cotton lint yield with the application of poultry litter (Adeli et al., 2019; Reddy et al., 2004). On the contrary, the high carbon-nitrogen ratio of the biochar may have led to N immobilization at the early vegetative stage in 2022 and 2023, resulting in a decline in cotton yield (Abban-Baidoo et al., 2024; Bossolani et al., 2023). The similar cotton yield and cottonseed yield for the CT and RT plots demonstrate that strip tillage is as effective as CT in seedbed preparation in cotton production (Ankomah et al., 2024).

4.3.2.2. Peanut biomass and yield

The management systems significantly affected the peanut biomass but not the yield (Table S4.5). In 2022, the RT+CR+PL and RT+CR+PL+BC significantly had higher peanut biomass than the CT and RT. However, the RT+CR had similar biomass as the CT and RT (Figure 4.3). The higher biomass recorded for the RT+CR+PL and RT+CR+PL+BC could be due to the addition of PL, as the CT, RT, and RT+CR did not receive any nutrient source. However, the higher accumulation of biomass did not translate into an increase in yield. Peanut is a low-input crop, requiring minimal nutrients (Monfort et al., 2022), which possibly explains why the plots that received PL (RT+CR+PL and RT+CR+PL+BC) did not have significantly higher yields than the plots that received no form of nutrients (CT, RT, RT+CR). Moreover, the application of PL in peanut production in Georgia, USA, is an uncommon practice (Monfort et al., 2022). We applied PL in the peanut phase to enable us to assess the cumulative impacts of the management systems on all three row crops. The RT had a similar yield as the CT in all years, indicating strip tillage can be implemented in peanut production without adversely affecting yields (Figure 4.3d, e, f). Tilling only the plant rows in the RT potentially loosened the soil and enhanced germination, plant establishment, pod formation, and pegging to levels comparable to the CT (Lopes de Brito Filho et al., 2023).

4.3.2.3. Corn biomass and yield

The management systems had no significant effect on corn biomass and yield (Table S4.5). Despite the lack of significant differences, including PL in RT and CR (RT+CR+PL) tended to have higher corn residual biomass compared to the other management systems in 2021 and 2022 (Figure 4.4a, b). However, in 2023, the RT+CR+PL had the least corn biomass accumulation, with the CT, RT, and RT+CR accumulating 18%, 18%, and 25% more biomass, respectively. In 2021 and 2022, the RT+CR+PL plots received the full rates of the inorganic fertilizer in addition to nutrients from the PL, which possibly explains the higher biomass accumulation. However, in 2023, the nutrients in the PL were accounted for and supplemented with a reduced amount of the inorganic fertilizer (Table S4.1, S4.3). Moreover, in 2023, the RT+CR+PL plots received 33% of the inorganic N applied at the initial stage (V3; three-leaf collar stage) compared to 60% applied for CT, RT, and RT+CR, and 50% for RT+CR+PL+BC (Tables S4.3). It was expected that the N in the PL of the RT+CR+PL plots would be released to supplement the inorganic N applied. However, the mineralization of N from PL is highly dependent on environmental and edaphic factors (Cassity-Duffey et al., 2020; Lazicki et al., 2020), and it is possible that N mineralization did not synchronize with crop demand. Even though corn nutrient uptake is low up to the V6 (six-leaf collar) stage, early nutrient stress may have reduced biomass accumulation for the RT+CR+PL in 2023. Additionally, corn may not recover from early nutrient stress, and yield could be adversely affected (Amissah, Ankomah, Lee, Perry et al., 2024). While no significant differences were evident, early nutrient stress could account for the slight yield decrease for RT+CR+PL in 2023 (Figure 4.4f). The RT performed similarly to the CT in terms of corn yield, which shows strip tillage is as effective as CT in seedbed preparation (Figure 4.4d, e, f).

4.3.3. Crop quality

The management systems had a minimal effect on the cotton fiber quality indicators, with a significant effect observed only for the +b (fiber yellowness; Table S4.6). Also, the physical quality indicators of peanut kernels were not affected by the management systems (Table S4.7). There were only a few instances where the management systems had a significant effect on the protein and nutrient content of peanut seed, hull, and corn seed, as indicated by the test statistics (Table S8). The management systems had a significant effect on the Cu and Mo content of peanut seed in 2023 and the Mo content of the hull in 2022 and 2023 (Table S4.8). The Mn, Cu, and Mo content of corn seed in 2023 was significantly affected by the management systems (Table S4.8).

4.3.3.1. Cotton fiber and peanut kernel quality indicators

Except for the +b (fiber yellowness), the cotton fiber quality indicators showed no significant differences between the management systems (Table 4.2). In 2022, while the RT+CR+PL treatment showed a slightly higher +b value compared to RT+CR and RT+CR+PL+BC, these differences were marginal, remaining below 5%. Overall, the differences in all the fiber quality parameters among the various management systems were small and will not adversely impact the grading class. For instance, the fiber strength is classified as strong or very strong for all the management systems. Also, the fiber length uniformity is classified as average or high for all the management systems (USDA-AMS, 2018). This suggests that the various regenerative agricultural practices did not improve the fiber quality indicators better than the CT. Our findings align with a three-year study conducted by Ankomah et al. (2024), who found that integrating CR, PL, and BC into both CT and RT had little impact on cotton fiber quality parameters.

No significant differences were observed in the physical quality indicators of peanut kernels when comparing the management systems (Table 4.3). Moreover, the TSMK for all the management systems was acceptable (more than 70%). The TSMK is a key parameter that affects the dollar value of peanut (Monfort et al., 2022; USDA, 2019). The lack of differences in the

TSMK, therefore, suggests that, apart from RT, adopting the other regenerative agricultural practices (CR, PL, and BC) in peanut production systems may not be profitable. There is a minimum number of tillage passes for RT, as only the plant rows are tilled compared to the CT. As a result, RT could result in decreased fuel use and lower costs associated with tillage operations compared to CT (Che et al., 2023). In contrast, incorporating CR, PL, and BC would likely increase production costs, given that they are additional inputs.

4.3.3.2. Protein and nutrient content of peanut seeds, hull, and corn seeds

In 2022 and 2023, the RT+CR+PL and RT+CR+PL+BC tended to enrich the Cu and Mo of peanut seed and hull, but the differences were not always consistent when compared to the other management systems (Table 4.4, 4.5). Similarly, in 2023, the CT and RT+CR+PL had higher Mn content of corn seed compared to RT, RT+CR, and RT+CR+PL+BC. While the RT+CR also showed lower Mn content, the differences were not statistically significant (Table 4.6). Additionally, the Cu content in the corn seed of the CT, RT+CR, and RT+CR+PL was significantly higher than the RT and RT+CR+PL+BC in 2023. Also, the Mo content in corn seed for the RT+CR+PL and RT+CR+PL+BC was higher compared to the CT and RT+CR. The Cu and Mo released from the PL may have directly increased the concentration of these nutrients in the peanut seed and hull. Also, the continuous application of PL in the RT+CR+PL plots for three years resulted in higher or similar levels of Mn, Cu, and Mo in corn seed compared to the other management systems. Overall, there were marginal differences in the protein and macronutrient

(P, K, Mg, Ca, and S) content of peanut seeds, hull, and corn seeds, indicating none of the management systems was a major driver of these quality indicators. We expected the nutrients released from the PL, especially during the late season of corn growth, to enrich the seed, but this was not observed in our study. Our findings are partly supported by Tewolde et al. (2019), who revealed that PL did not enrich the N, P, K, and Mg content of corn seed. Tewolde et al. (2019), also indicated that N or protein concentrations of corn seed were highly and positively correlated with the concentrations of the other nutrients. It is not surprising that we did not observe differences in the protein as well as the macronutrients.

4.3.4. Nutrient uptake in residual biomass

The management systems had a significant effect on only Cu uptake in cotton biomass in 2021 (Table S4.9). The management systems significantly influenced the C accumulated in peanut biomass in 2022 (Table S4.9). Additionally, the management systems significantly impacted the uptake of P in peanut biomass in 2022 and 2023; K in 2021, 2022, and 2023; Mg in 2022 and 2023; B in 2022; Zn in 2023; Mn in 2021; and Mo in 2021, 2022, and 2023. The test statistics (Table S4.9) revealed that the management systems influenced the uptake of P, K, and Mg in corn biomass in 2022; S and Zn in 2023; Mn in both 2022 and 2023; and Mo in 2021 and 2022.

4.3.4.1. Nutrient uptake in cotton and peanut residual biomass

Significant differences were observed for only Cu uptake in cotton biomass in 2021 (Table 4.7). The RT+CR+PL had more Cu uptake, with significant differences observed when compared to the RT. Despite observing no significant differences, the application of PL in RT and CR (RT+CR+PL) tended to consistently have higher accumulation of all nutrients (except Zn and Mn in 2023) in cotton biomass in all years compared to RT+CR (Table 7). The application of PL potentially enriched the soil nutrients and enhanced the mineralization of CR (Mitchell and Tu 2006; Poffenbarger et al., 2015). Moreover, cotton followed peanut in rotation in 2022 and 2023, and the cotton in the RT+CR+PL plots may have utilized the residual nutrients of the PL applied in the peanut phase. This is particularly relevant because peanut can fix N and are good scavengers of nutrients, particularly P and K (Monfort et al., 2022). As a result, the peanut crop probably utilized less of the nutrients released from the poultry litter, leaving more available for the subsequent cotton crop.

Differences were observed in the nutrient uptake in peanut biomass (Table 4.8). In 2022, the RT+CR+PL and RT+CR+PL+BC had more carbon accumulated in peanut biomass compared to the other management systems. The N and P uptake followed a similar trend as the C uptake, but the differences in the N uptake were not significant. Also, in 2023, the P uptake for the RT+CR+PL was significantly higher than the CT. The K uptake in peanut biomass in 2021, 2022, and 2023 was higher in the RT+CR+PL and RT+CR+PL+BC plots compared to the other management systems, but the differences were not always significant. In 2022 and 2023, the Mg uptake in peanut biomass for the RT+CR+PL and RT+CR+PL+BC was relatively higher compared to the other management systems, with significant differences observed when the RT+CR+PL is compared to the CT and RT in 2022 and RT+CR in 2023 (Table 4.8). A similar trend was observed for the B uptake in 2022, where the RT+CR+PL significantly had higher uptake compared to the CT and RT. The Zn uptake in peanut biomass for the RT, RT+CR, and RT+CR+PL+BC was significantly higher than the CT in 2023. In 2021, the Mn uptake for the RT was significantly higher than the CT. The RT+CR+PL had higher Mo uptake in peanut biomass in 2021, 2022, and 2023 compared to the other management systems. However, in 2021, the Mo uptake was only significant when the RT+CR+PL was compared to the RT. Overall, the RT+CR+PL and RT+CR+PL+BC tended to have higher uptake of the P, K, and Mg in the second and third years of the study compared to the other management systems. The continuous application of PL potentially increased the concentration of these soil nutrients, subsequently enhancing their uptake in peanut biomass (Mitchell and Tu, 2006). Despite the differences in nutrient uptake, it did not increase peanut yield (Figure 4.3d, e, f).

4.3.4.2. Nutrient uptake in corn residual biomass

No significant differences were observed in the C and N accumulated in corn biomass across the management systems (Table 4.9). Despite the lack of significant differences, in 2021 and 2022, the RT+CR+PL had higher C and N accumulated in corn biomass compared to the other management systems. The RT+CR+PL had 15-25% and 3-17% more C accumulated in corn biomass in 2021 and 2022, respectively. In 2021, the RT+CR+PL had 20%, 35%, 12%, and 16% more N accumulated than the CT, RT, RT+CR, and RT+CR+PL+BC, respectively. Similarly, in 2022, the N accumulated in corn biomass for the RT+CR+PL was 10%, 12%, 13%, and 20% more than the CT, RT, RT+CR, and RT+CR+PL+BC, respectively. In 2022, RT+CR+PL had a higher P uptake in corn than the other management systems, with significant differences observed when compared to the CT and RT+CR+PL+BC (Table 4.9). Similarly, the K uptake for RT+CR+PL in 2022 was higher than that of the other management systems. Studies have reported an increased N, P, and K uptake in corn biomass with the application of PL (Adeli et al., 2012; Novak et al., 2021; Sistani et al., 2014).

An opposite trend was observed for the Mg uptake in 2022, where the RT+CR+PL and RT+CR+PL+BC had the least uptake (Table 4.9). In 2023, the RT+CR accumulated more S and Zn compared to the other management systems, but the differences were not always significant. The Mn uptake in 2022 for the RT and RT+CR was significantly higher than the other management systems, with the RT significantly having higher levels than the RT+CR+PL+BC. In 2023, the RT+CR had higher Mn uptake than the other management systems, but the differences were only significant when compared to the CT. The Mo uptake in 2021 and 2022 was highest for the RT+CR+PL, however, when compared to that of the RT+CR+PL+BC in 2022, the difference was not significant. Despite observing differences in the nutrient uptake, it did not translate to an increase in corn grain yield (Figure 4.4d, e, f).

4.4. Conclusions

The management systems had a minimal impact on row crop productivity and quality. Applying PL in RT and CR (RT+CR+PL) in the first year (2021) tended to result in higher biomass accumulation compared to the other management systems in 2021. The plots that received PL (RT+CR+PL and RT+CR+PL+BC) increased the cotton lint yield and cottonseed yield in 2021, with significant differences observed only for the cottonseed yield. Despite no significant difference, the RT+CR+PL tended to increase cottonseed yield and lint yield in 2022 and 2023 compared to the RT+CR, but further adding BC (RT+CR+PL+BC) decreased the yields. The nutrients supplied by the PL potentially increased cotton yield, particularly in 2023, as no inorganic fertilizer was applied. In contrast, the high carbon-nitrogen ratio of the biochar may have led to nutrient immobilization at the early vegetative stage, resulting in a decline in cotton yield. The RT+CR+PL and RT+CR+PL+BC increased peanut biomass in 2022, but the higher accumulation of biomass did not translate into an increase in yield. Applying PL together with full inorganic fertilizer rates (RT+CR+PL) in the first two years tended to increase corn biomass accumulation but did not increase corn yield. Also, accounting for the nutrients in the PL and applying reduced amounts of the inorganic fertilizer rates in the third year tended to decrease biomass accumulation and corn yield. The RT had similar cotton, peanut, and corn yields as the CT, indicating that strip tillage was effective in seedbed preparation. The PL plots tended to have enriched Cu and Mo in peanut seed and hull. Differences in the nutrient uptake in crop biomass, particularly corn and peanut, did not translate into an increase in crop yield.

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Tables

Table 4.1: Initial soil properties of the 0-15 cm and 15-30 cm soil depths of the study site.

Soil depth	OM	pH	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu
cm	g kg^{-1}		---------------------------------- mg kg^{-1} --------------------------------------								
0-15	8.6	6.64	45.6	37.4	29.8	303	0.19	4.34	16.8	28.3	1.98
15-30	8.3	6.71	44.4	31.1	22.1	315	0.19	3.76	14.4	26.5	1.65

Abbreviations: OM, organic matter.

Table 4.2: Impact of management systems on cotton fiber quality indicators in 2021, 2022, and 2023.

Management systems	Fiber length	Fiber strength	Micronaire	Uniformity	Rd	+b
	cm	g tex^{-1}		%	%	
			2021			
CT	3.12±0.03a	29.8±0.4a	4.15±0.06a	82.2±0.5a	78.2±0.6a	7.32±0.07a
RT	3.14±0.02a	30.2±0.4a	4.25±0.06a	82.3±0.2a	78.6±0.7a	7.42±0.17a
RT+CR	3.12±0.02a	29.7±0.4a	4.15±0.03a	82.0±0.3a	78.9±0.3a	7.22±0.02a
RT+CR+PL	3.13±0.03a	30.1±0.4a	4.12±0.05a	82.3±0.5a	79.1±0.4a	7.38±0.06a
RT+CR+PL+BC	3.17±0.02a	30.1±0.2a	4.02±0.05a	82.2±0.4a	78.8±0.3a	7.30±0.14a
			2022			
CT	3.00±0.03a	32.0±0.4a	4.30±0.12a	83.8±0.2a	74.4±0.5a	7.85±0.05ab
RT	3.00±0.04a	33.2±0.2a	4.35±0.06a	83.8±0.3a	74.3±0.2a	7.75±0.10ab
RT+CR	2.98±0.02a	33.0±0.3a	4.35±0.03a	83.5±0.2a	74.7±0.2a	7.70±0.04b
RT+CR+PL	3.02±0.03a	32.9±0.5a	4.25±0.13a	83.3±0.3a	74.5±0.2a	7.97±0.05a
RT+CR+PL+BC	3.00±0.03a	33.3±0.3a	4.38±0.09a	84.0±0.3a	74.5±0.6a	7.68±0.13b
			2023			
CT	3.04±0.02a	32.0±0.4a	3.62±0.10	82.4±0.4a	79.7±0.1a	6.62±0.13a
RT	3.06±0.02a	31.7±0.6a	3.55±0.10a	82.7±0.4a	80.2±0.2a	6.72±0.15a
RT+CR	3.02±0.01a	32.1±0.3a	3.62±0.05a	82.3±0.3a	80.1±0.1a	6.70±0.10a
RT+CR+PL	3.08±0.03a	32.1±0.2a	3.62±0.05a	83.2±0.2a	80.1±0.2a	6.80±0.07a
RT+CR+PL+BC	3.04±0.02a	31.6±0.2a	3.55±0.10a	83.1±0.2a	80.1±0.2a	6.82±0.09a

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error (n = 4). CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar. Rd: fiber reflectance; +b: fiber yellowness.

Table 4.3: Impact of management systems on the physical quality indicators of peanut kernels in 2021, 2022, and 2023.

Management systems	SMK	SS	TSMK	OK
	%			
	2021			
CT	73.5±0.9a	2.50±0.65a	76.0±0.4a	2.00±0.41a
RT	73.2±0.5a	2.75±0.48a	76.0±0.4a	2.25±0.25a
RT+CR	73.0±0.4a	3.00±0.41a	76.0±0.4a	2.25±0.25a
RT+CR+PL	73.2±0.2a	2.25±0.25a	75.5±0.5a	2.25±0.25a
RT+CR+PL+BC	72.0±0.4a	3.00±0.00a	75.0±0.4a	2.50±0.29a
	2022			
CT	71.2±0.7a	4.49±0.55a	75.7±0.6a	1.36±0.13a
RT	71.2±0.6a	3.74±0.41a	75.0±0.3a	1.79±0.13a
RT+CR	71.0±0.9a	4.34±0.62a	75.3±0.7a	1.78±0.36a
RT+CR+PL	69.0±1.2a	4.39±0.50a	73.4±0.8a	2.19±0.30a
RT+CR+PL+BC	70.6±0.9a	4.25±0.54a	74.9±0.6a	1.95±0.12a
	2023			
CT	70.5±0.3a	2.52±0.23a	73.0±0.3a	1.51±0.10a
RT	70.2±0.5a	2.15±0.18a	72.3±0.3a	1.57±0.11a
RT+CR	70.2±0.4a	2.34±0.19a	72.5±0.3a	1.53±0.16a
RT+CR+PL	70.5±1.1a	2.24±0.14a	72.8±1.2a	1.90±0.15a
RT+CR+PL+BC	71.2±0.5a	2.12±0.18a	73.3±0.4a	1.64±0.15a

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error (n = 4). CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.
SMK: sound mature kernels; SS: sound split; TSMK: total sound mature kernels; OK: other kernels.

Table 4.4: Impact of management systems on protein and nutrient content of peanut seeds in 2022 and 2023.

Management systems	Protein	P	K	Mg	Ca	S	Zn	Mn	Fe	Cu	Mo
	%	---------- g kg^{-1} ----------					---------- mg kg^{-1} ----------				
	---------- 2022 ----------										
CT	24.4±0.6a	4.40±0.07a	6.66±0.06a	1.99±0.02a	0.84±0.11a	1.70±0.01a	43.5±0.8a	18.6±0.8a	11.1±1.8a	5.71±0.22a	0.53±0.04a
RT	26.6±0.7a	4.60±0.09a	6.59±0.14a	1.90±0.11a	0.82±0.08a	1.67±0.02a	48.5±1.5a	20.0±0.6a	11.3±2.3a	6.04±0.77a	0.58±0.22a
RT+CR	25.7±1.4a	4.68±0.25a	6.63±0.17a	2.01±0.10a	0.84±0.08a	1.79±0.07a	51.7±2.0a	20.7±1.3a	12.6±4.8a	6.21±0.51a	0.37±0.04a
RT+CR+PL	26.2±0.8a	4.99±0.09a	7.29±0.53a	1.94±0.13a	0.77±0.05a	1.81±0.03a	47.1±3.2a	18.6±3.3a	14.0±3.7a	7.67±0.62a	1.03±0.38a
RT+CR+PL+BC	26.1±1.3a	4.74±0.07a	6.94±0.07a	2.05±0.03a	0.74±0.05a	1.78±0.02a	49.6±2.5a	20.9±0.9a	11.6±1.2a	6.72±0.39a	0.96±0.18a
	---------- 2023 ----------										
CT	25.3±0.5a	4.26±0.05a	5.27±0.08a	1.85±0.03a	0.78±0.02a	1.56±0.01a	37.5±1.8a	16.4±0.5a	16.0±1.0a	4.66±0.26ab	0.55±0.04b
RT	24.7±0.5a	4.44±0.05a	5.49±0.05a	1.99±0.04a	0.74±0.05a	1.55±0.02a	39.3±2.2a	18.3±1.0a	15.6±1.4a	4.51±0.48ab	0.42±0.05b
RT+CR	25.1±0.6a	4.41±0.07a	5.41±0.13a	1.87±0.06a	0.73±0.05a	1.56±0.03a	40.0±1.3a	17.5±0.2a	15.1±0.5a	4.28±0.31b	0.54±0.05b
RT+CR+PL	25.1±0.3a	4.41±0.13a	5.52±0.17a	1.95±0.05a	0.76±0.04a	1.56±0.01a	36.5±1.5a	17.2±0.1a	13.1±0.4a	5.53±0.46ab	1.24±0.15a
RT+CR+PL+BC	24.5±0.8a	4.44±0.08a	5.51±0.07a	1.91±0.05a	0.70±0.01a	1.56±0.02a	39.5±0.5a	16.4±0.6a	13.8±0.5a	5.82±0.38a	1.04±0.01a

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error (n = 4). CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table 4.5: Impact of management systems on protein and nutrient content of peanut hull in 2022 and 2023.

Management systems	Protein	P	K	Mg	Ca	S	Zn	Mn	Fe	Cu	Mo
	%	---- g kg^{-1} ----					---- mg kg^{-1} ----				
	---- 2022 ----										
CT	4.98±0.40a	0.58±0.05a	7.50±0.57a	0.69±0.04a	2.84±0.19a	0.86±0.05a	23.2±1.6a	36.2±1.4a	313±35a	6.73±0.65a	0.20±0.02c
RT	5.25±0.19a	0.62±0.03a	7.77±0.33a	0.73±0.03a	2.94±0.12a	0.89±0.02a	30.3±2.3a	41.1±1.5a	414±52a	6.40±0.33a	0.26±0.01bc
RT+CR	5.31±0.33a	0.60±0.03a	7.63±0.17a	0.69±0.04a	2.96±0.11a	0.94±0.05a	27.5±0.7a	41.1±0.6a	357±51a	6.62±0.43a	0.23±0.02bc
RT+CR+PL	6.39±0.38a	0.67±0.06a	7.67±0.40a	0.76±0.08a	2.92±0.29a	0.91±0.08a	30.5±5.0a	39.4±0.3a	377±52a	7.62±0.42a	0.45±0.05a
RT+CR+PL+BC	5.94±0.13a	0.66±0.05a	7.62±0.28a	0.70±0.04a	2.72±0.22a	0.90±0.05a	28.3±2.2a	39.9±1.1a	328±46a	7.52±0.49a	0.33±0.05ab
	---- 2023 ----										
CT	5.42±0.34a	0.66±0.03a	6.95±0.13a	0.80±0.03a	2.54±0.11a	0.81±0.02a	18.0±2.8a	33.5±1.2a	218±36a	5.28±0.45a	0.17±0.01b
RT	5.58±0.71a	0.66±0.05a	6.95±0.32a	0.80±0.03a	2.28±0.10a	0.77±0.02a	18.6±2.0a	34.6±1.6a	201±14a	5.34±0.27a	0.22±0.03ab
RT+CR	5.42±0.19a	0.69±0.04a	7.09±0.23a	0.81±0.04a	2.47±0.12a	0.81±0.02a	15.6±1.0a	35.6±1.1a	201±32a	4.95±0.62a	0.19±0.03b
RT+CR+PL	5.98±0.61a	0.73±0.03a	7.34±0.20a	0.91±0.04a	2.55±0.08a	0.83±0.03a	17.2±3.0a	35.0±1.6a	253±77a	6.78±1.14a	0.43±0.09a
RT+CR+PL+BC	5.75±0.47a	0.73±0.07a	7.46±0.38a	0.86±0.08a	2.49±0.14a	0.82±0.05a	17.6±1.3a	33.2±1.0a	171±18a	7.10±0.59a	0.30±0.04ab

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error (n = 4). CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table 4.6: Impact of management systems on protein and nutrient content of corn seeds in 2021, 2022, and 2023.

Management systems	Protein	P	K	Mg	Ca	S	Zn	Mn	Fe	Cu	Mo
	%	g kg^{-1}					mg kg^{-1}				
2021											
CT	10.11±1.48a	3.39±0.49a	4.12±0.41a	0.91±0.12a	0.03±0.01a	1.14±0.14a	28.5±4.8a	9.14±1.93a	180±2a	1.09±0.14a	0.30±0.03a
RT	8.30±0.43a	2.93±0.17a	3.98±0.17a	0.75±0.03a	0.03±0.01a	1.05±0.01a	22.4±1.2a	7.53±1.06a	176±1a	0.97±0.24a	0.26±0.01a
RT+CR	8.42±0.66a	2.94±0.15a	3.83±0.25a	0.78±0.03a	0.02±0.01a	1.04±0.04a	22.8±1.4a	8.45±1.54a	177±1a	1.11±0.27a	0.29±0.02a
RT+CR+PL	9.33±1.48a	3.43±0.12a	4.56±0.10a	0.88±0.04a	0.05±0.02a	1.19±0.08a	23.9±1.1a	10.73±2.55a	175±2a	1.37±0.28a	0.30±0.02a
RT+CR+PL+BC	8.47±0.46a	2.97±0.13a	3.93±0.25a	0.81±0.05a	0.02±0.01a	1.10±0.07a	22.1±1.4a	7.06±0.50a	172±2a	1.24±0.30a	0.32±0.03a
2022											
CT	8.14±0.61a	2.66±0.08a	3.31±0.08a	0.78±0.03a	0.04±0.01a	1.11±0.01a	23.2±0.8a	5.38±0.14a	21.5±0.8a	1.85±0.57a	0.10±0.03a
RT	8.66±0.40a	2.82±0.34a	3.50±0.34a	0.81±0.10a	0.03±0.01a	1.10±0.09a	26.6±3.6a	6.87±0.75a	23.6±3.8a	1.16±0.22a	0.06±0.03a
RT+CR	7.62±0.52a	2.66±0.16a	3.39±0.20a	0.77±0.03a	0.02±0.01a	1.14±0.02a	24.1±2.1a	5.85±0.32a	22.1±1.9a	1.73±0.52a	0.09±0.03a
RT+CR+PL	7.83±0.47a	3.09±0.06a	3.70±0.04a	0.83±0.01a	0.03±0.00a	1.13±0.03a	23.4±1.0a	6.48±0.40a	24.6±4.8a	2.45±0.32a	0.18±0.02a
RT+CR+PL+BC	8.97±0.20a	2.78±0.15a	3.47±0.17a	0.77±0.04a	0.02±0.00a	1.10±0.05a	23.4±0.8a	5.66±0.36a	21.6±2.2a	3.37±1.15a	0.17±0.04a
2023											
CT	8.22±0.64a	4.24±0.60a	4.69±0.57a	1.37±0.27a	0.17±0.06a	1.47±0.19a	28.9±5.9a	7.01±0.87a	22.0±6.3a	1.90±0.49a	0.53±0.13b
RT	7.80±0.67a	2.50±0.04a	2.98±0.04a	0.73±0.03a	0.02±0.01a	0.85±0.09a	15.9±0.8a	1.25±0.08b	10.9±4.6a	0.42±0.17b	0.66±0.13ab
RT+CR	8.22±0.30a	4.28±0.98a	4.76±0.90a	1.29±0.31a	0.14±0.05a	1.28±0.18a	27.2±6.5a	4.85±1.93ab	16.0±9.5a	1.46±0.56a	0.48±0.10b
RT+CR+PL	8.45±0.30a	4.84±0.91a	5.53±0.90a	1.48±0.36a	0.14±0.05a	1.46±0.25a	29.2±5.8a	8.43±0.39a	29.0±5.9a	1.87±0.48a	0.81±0.12a
RT+CR+PL+BC	7.83±0.54a	2.92±0.37a	3.83±0.53a	0.86±0.13a	0.07±0.03a	1.02±0.12a	19.4±2.2a	2.38±0.75b	14.0±4.4a	0.74±0.31b	0.84±0.12a

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($p < 0.05$). Values represent the mean ± standard error (n = 4). CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biocha

Table 4.7: Impact of management systems on cotton biomass nutrient uptake in 2021, 2022, and 2023.

Management systems	C	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
	$Mg\ ha^{-1}$	$kg\ ha^{-1}$						$g\ ha^{-1}$					
2021													
CT	3.26±0.13a	52.3±5.6a	12.5±0.3a	149±82a	7.92±0.60a	52.7±4.9a	11.5±0.6a	196±16a	92.3±7.1a	155±11a	216±30a	11.3±0.5ab	4.81±0.41a
RT	2.71±0.42a	44.0±6.2a	11.3±1.7a	119±19a	6.45±1.02a	41.7±7.4a	9.1±1.4a	163±28a	68.1±10.2a	164±32a	120±21a	8.5±1.6b	3.84±0.60a
RT+CR	2.46±0.25a	34.0±2.5a	10.1±0.7a	112±12a	5.11±0.36a	37.2±4.2a	8.2±0.8a	139±14a	56.4±5.0a	113±7a	115±11a	10.2±0.9ab	3.67±0.40a
RT+CR+PL	3.78±0.36a	53.1±4.7a	14.2±2.8a	190±26a	8.36±0.82a	56.3±7.5a	13.5±2.1a	213±29a	70.8±4.4a	154±17a	267±111a	22.2±5.2a	6.30±1.18a
RT+CR+PL+BC	3.43±0.65a	48.4±8.6a	13.0±1.6a	160±34a	6.81±1.12a	48.7±10.7a	11.3±2.7a	182±36a	70.5±11.1a	147±26a	133±25a	13.3±2.0ab	5.10±0.89a
2022													
CT	2.01±0.22a	38.2±6.0a	8.05±1.11a	109±13a	7.28±1.40a	40.3±7.0a	11.0±1.7a	177±31a	53.1±6.4a	72.9±11.9a	134±31a	9.8±1.3a	2.64±0.26a
RT	1.86±0.31a	37.5±4.6a	7.98±1.20a	110±21a	6.43±1.06a	42.8±9.1a	11.2±1.9a	180±32a	50.2±7.9a	96.3±3.8a	124±20a	12.0±2.4a	2.50±0.47a
RT+CR	1.73±0.30a	34.1±6.1a	7.14±1.23a	98±18a	5.84±1.09a	37.2±6.8a	9.3±1.6a	156±29a	47.7±7.5a	89.2±7.4a	121±29a	10.1±2.0a	2.27±0.49a
RT+CR+PL	2.06±0.23a	46.8±3.8a	10.40±1.23a	129±13a	7.35±0.96a	47.6±5.1a	12.4±1.2a	194±19a	65.5±5.9a	101.1±24.6a	152±18a	14.2±1.6a	3.13±0.41a
RT+CR+PL+BC	1.98±0.33a	42.4±11.1a	9.09±2.10a	122±25a	7.22±1.58a	48.2±10.3a	12.6±3.1a	197±44a	62.7±18.1a	114.7±28.2a	159±31a	14.5±3.4a	2.96±0.77a
2023													
CT	2.74±0.12a	53.5±4.8a	10.18±0.44a	180±13a	7.86±0.23a	69.4±5.1a	19.9±1.3a	219±13a	70.3±7.1a	87.9±8.7a	187±30a	14.8±4.3a	3.82±0.04a
RT	2.16±0.10a	42.1±1.7a	8.77±0.46a	150±11a	6.50±0.35a	56.0±2.0a	15.6±0.7a	176±11a	62.8±4.5a	99.0±7.8a	170±15a	10.1±1.2a	3.25±0.34a
RT+CR	2.18±0.24a	44.6±3.4a	9.99±1.77a	155±28a	5.88±1.21a	54.1±8.8a	15.5±3.2a	182±29a	70.8±10.2a	91.3±14.1a	162±32a	11.2±2.9a	3.34±0.91a
RT+CR+PL	2.39±0.24a	52.8±2.9a	11.29±1.44a	166±20a	6.48±0.66a	62.3±8.1a	18.2±2.3a	202±25a	68.2±7.0a	86.7±7.7a	181±36a	15.6±2.8a	4.11±0.47a
RT+CR+PL+BC	2.00±0.21a	48.2±7.0a	9.57±0.92a	141±16a	5.16±0.63a	54.6±8.6a	15.9±2.5a	182±26a	59.1±6.8a	86.0±20.2a	166±29a	11.1±1.5a	3.29±0.33a

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error (n = 4). CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table 4.8: Impact of management systems on peanut biomass nutrient uptake in 2021, 2022, and 2023.

Management systems	C	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
	Mg ha^{-1}	kg ha^{-1}						g ha^{-1}					
2021													
CT	2.28±0.17a	88.6±5.5a	9.74±0.91a	162±9b	21.9±1.4a	102±6a	8.09±0.70a	225±6a	361±79a	216±31b	1274±464a	19.2±0.5a	1.32±0.07b
RT	2.46±0.10a	91.6±6.2a	10.95±0.93a	192±2ab	19.2±0.8a	115±1a	8.80±0.27a	243±14a	488±47a	419±30a	938±102a	34.6±6.0a	1.25±0.08b
RT+CR	2.23±0.41a	80.1±13.9a	9.89±2.07a	166±31b	17.5±3.4a	103±19a	7.59±1.32a	208±39a	506±194a	248±29ab	1133±489a	21.0±4.2a	1.31±0.32b
RT+CR+PL	2.46±0.18a	89.8±7.0a	8.80±0.53a	232±9a	18.9±0.6a	102±6a	8.30±0.46a	238±17a	478±75a	345±45ab	1198±249a	25.1±3.9a	3.49±0.21a
RT+CR+PL+BC	2.49±0.13a	91.8±5.7a	9.08±0.83a	226±13a	17.4±1.2a	102±6a	8.45±0.28a	239±17a	417±73a	387±75ab	732±80a	22.4±0.3a	3.74±1.00a
2022													
CT	2.46±0.31b	88.1±8.5a	9.62±1.46b	226±23b	19.8±1.4b	101±7a	10.5±1.2a	212±18b	261±27a	190±78a	1199±100a	22.0±1.5a	1.13±0.23c
RT	2.48±0.15b	94.6±10.0a	9.10±0.60b	220±13b	20.2±1.2b	103±5a	10.4±0.4a	220±18b	488±72a	314±63a	1016±117a	26.2±1.6a	0.70±0.12c
RT+CR	2.79±0.12ab	100.5±8.5a	9.89±0.71b	236±11b	21.9±1.5ab	114±8a	10.8±0.4a	235±10ab	472±57a	354±32a	1164±52a	31.5±3.9a	0.91±0.15c
RT+CR+PL	3.13±0.18a	123.4±12.0a	12.07±0.73a	280±17a	26.6±1.8a	119±3a	10.8±0.3a	283±10a	429±55a	256±49a	1267±126a	29.3±1.1a	6.73±0.65a
RT+CR+PL+BC	3.14±0.13a	114.4±8.6a	12.28±0.48a	278±6a	24.2±1.7ab	122±6a	12.1±0.3a	267±14ab	425±47a	256±47a	1185±87a	31.8±2.5a	4.86±0.30b
2023													
CT	2.32±0.14a	93.4±5.2a	10.0±0.4b	165±13ab	21.1±0.9ab	99±6a	9.8±0.7a	213±11a	152±14b	156±12a	1094±103a	11.0±1.8a	1.60±0.19c
RT	2.50±0.07a	97.5±5.5a	11.4±0.6ab	172±17ab	21.6±1.1ab	101±7a	10.5±0.6a	226±14a	330±41a	329±42a	1040±76a	10.6±2.2a	1.08±0.23c
RT+CR	2.32±0.18a	84.8±3.8a	10.9±0.3ab	145±14b	19.4±1.5b	98±4a	9.6±0.4a	201±16a	292±13a	292±35a	1056±291a	14.4±2.2a	1.18±0.09c
RT+CR+PL	2.78±0.14a	107.4±7.0a	13.6±0.5a	218±20a	26.5±1.6a	104±7a	10.7±0.6a	259±23a	223±9ab	234±70a	919±145a	16.0±4.8a	14.35±0.98a
RT+CR+PL+BC	2.56±0.09a	96.1±2.8a	11.9±0.7ab	182±6ab	22.8±1.2ab	103±4a	10.1±0.4a	226±10a	316±39a	218±32a	782±25a	15.9±2.8a	6.24±1.03b

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error (n = 4). CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table 4.9: Impact of management systems on corn biomass nutrient uptake in 2021, 2022, and 2023.

Management systems	C	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
	Mg ha^{-1}	kg ha^{-1}						g ha^{-1}					
2021													
CT	4.10±0.30a	62.8±2.6a	5.81±0.99a	225±24a	9.72±1.74a	32.7±3.4a	8.25±0.90a	69.6±2.5a	188±32a	720±214a	404±56a	23.7±5.4a	1.89±0.16b
RT	4.47±0.30a	55.9±5.4a	5.15±0.31a	251±21a	7.60±1.01a	35.8±5.4a	8.27±0.47a	78.9±4.8a	195±15a	695±75a	557±126a	26.1±5.8a	1.61±0.15b
RT+CR	4.28±0.14a	67.0±5.6a	5.15±0.29a	252±20a	8.29±0.76a	35.9±3.2a	8.50±0.65a	73.4±5.5a	209±41a	774±91a	382±11a	27.8±4.3a	2.03±0.16b
RT+CR+PL	5.13±0.39a	75.3±7.3a	8.05±1.62a	339±15a	8.36±1.40a	32.2±4.0a	10.02±0.97a	74.6±7.1a	197±32a	738±82a	426±23a	44.5±4.7a	3.62±0.27a
RT+CR+PL+BC	4.36±0.39a	65.0±6.7a	5.90±0.80a	252±17a	9.30±1.70a	33.3±3.7a	8.64±0.71a	81.0±8.7a	209±27a	621±60a	408±78a	40.8±6.8a	2.76±0.50ab
2022													
CT	4.33±0.14a	82.7±5.5a	6.88±0.72b	219±5b	13.67±0.85a	52.1±1.4a	9.2±0.5a	85.0±10.5a	290±33a	896±80ab	2278±202a	44.5±8.5a	1.00±0.25c
RT	4.25±0.24a	81.2±4.7a	8.95±1.64ab	246±22b	11.38±1.46ab	52.4±3.6a	11.3±1.9a	98.4±19.9a	386±32a	1341±154a	2226±141a	58.9±13.0a	1.32±0.18bc
RT+CR	4.70±0.07a	80.1±2.8a	10.28±1.56ab	249±24b	13.26±1.25a	55.6±2.7a	11.2±1.4a	85.3±15.6a	338±36a	1079±85ab	2349±131a	53.2±12.0a	1.76±0.41bc
RT+CR+PL	4.83±0.38a	90.8±7.0a	11.78±0.95a	326±32a	9.88±1.02b	46.2±3.7a	10.8±1.4a	92.1±22.5a	279±27a	896±131ab	2655±429a	61.2±10.1a	4.12±0.38a
RT+CR+PL+BC	4.13±0.12a	75.9±2.5a	7.52±0.36b	255±11b	9.72±1.03b	44.5±2.4a	9.4±0.4a	83.4±7.4a	297±21a	868±69b	2053±131a	50.1±4.7a	2.32±0.35b
2023													
CT	2.83±0.05a	44.9±2.2a	5.39±1.63a	84.3±23.5a	9.90±3.25a	14.4±4.2a	7.21±1.80ab	16.3±4.1a	123±40ab	130±45b	291±121a	28.7±12.1a	4.41±0.35a
RT	2.83±0.14a	41.1±4.0a	5.14±1.34a	63.5±14.4a	7.39±2.41a	17.0±6.6a	5.25±0.84b	15.0±1.5a	110±34b	145±58ab	223±87a	16.4±8.0a	3.69±0.49a
RT+CR	3.01±0.15a	43.7±0.7a	8.17±1.44a	102.5±18.2a	12.23±2.67a	16.3±3.2a	8.87±1.01a	29.4±4.7a	202±44a	247±56a	440±175a	39.7±5.8a	4.21±0.82a
RT+CR+PL	2.42±0.14a	37.8±4.9a	6.54±1.90a	85.2±16.1a	7.69±1.38a	15.1±2.5a	7.02±1.01ab	18.8±2.4a	124±25ab	184±38ab	287±58a	38.9±8.9a	4.72±1.00a
RT+CR+PL+BC	2.53±0.17a	39.3±7.4a	4.18±0.81a	65.9±20.3a	6.43±2.32a	10.9±2.8a	5.16±1.18b	15.2±6.5a	100±29b	145±46ab	265±97a	21.1±8.6a	3.55±0.57a

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error (n = 4). CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Figures

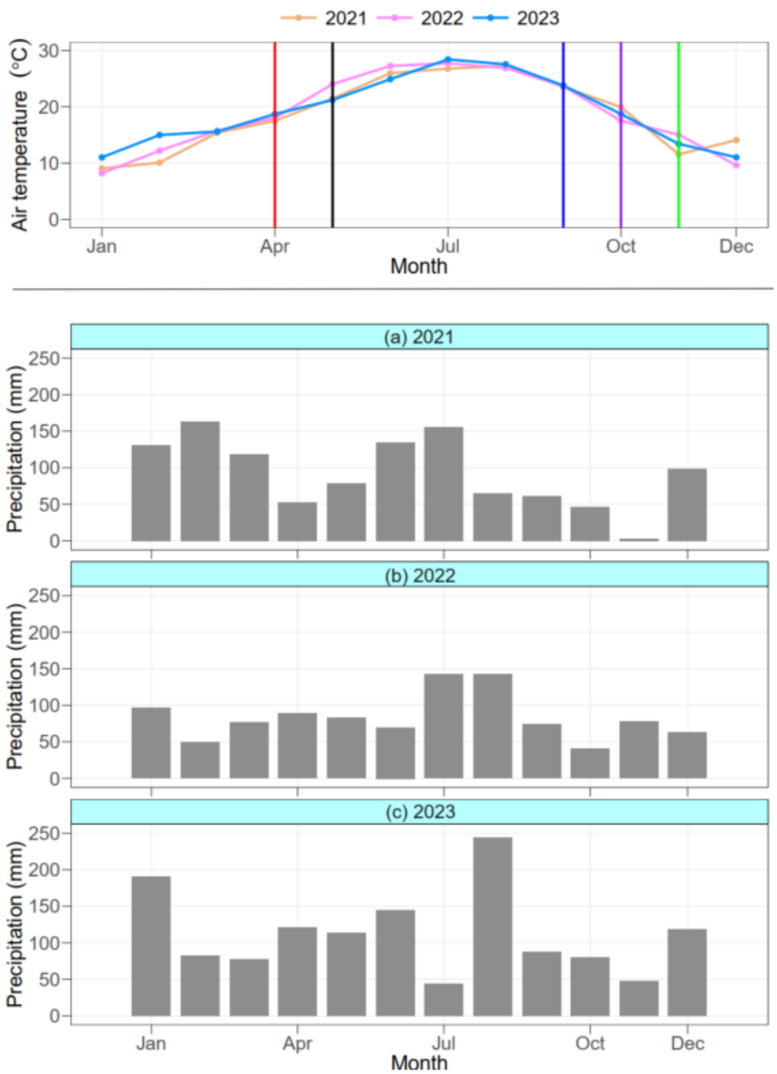

Figure 4.1. Monthly average temperature (top) and the monthly total precipitation in Midville, GA, from 2021 to 2023 (a, b, c). The solid red and blue vertical lines represent the planting and harvesting months for corn, respectively. Similarly, the solid black and violet vertical lines denote the planting and harvesting months for peanut, while the solid black and green vertical lines indicate those for cotton.

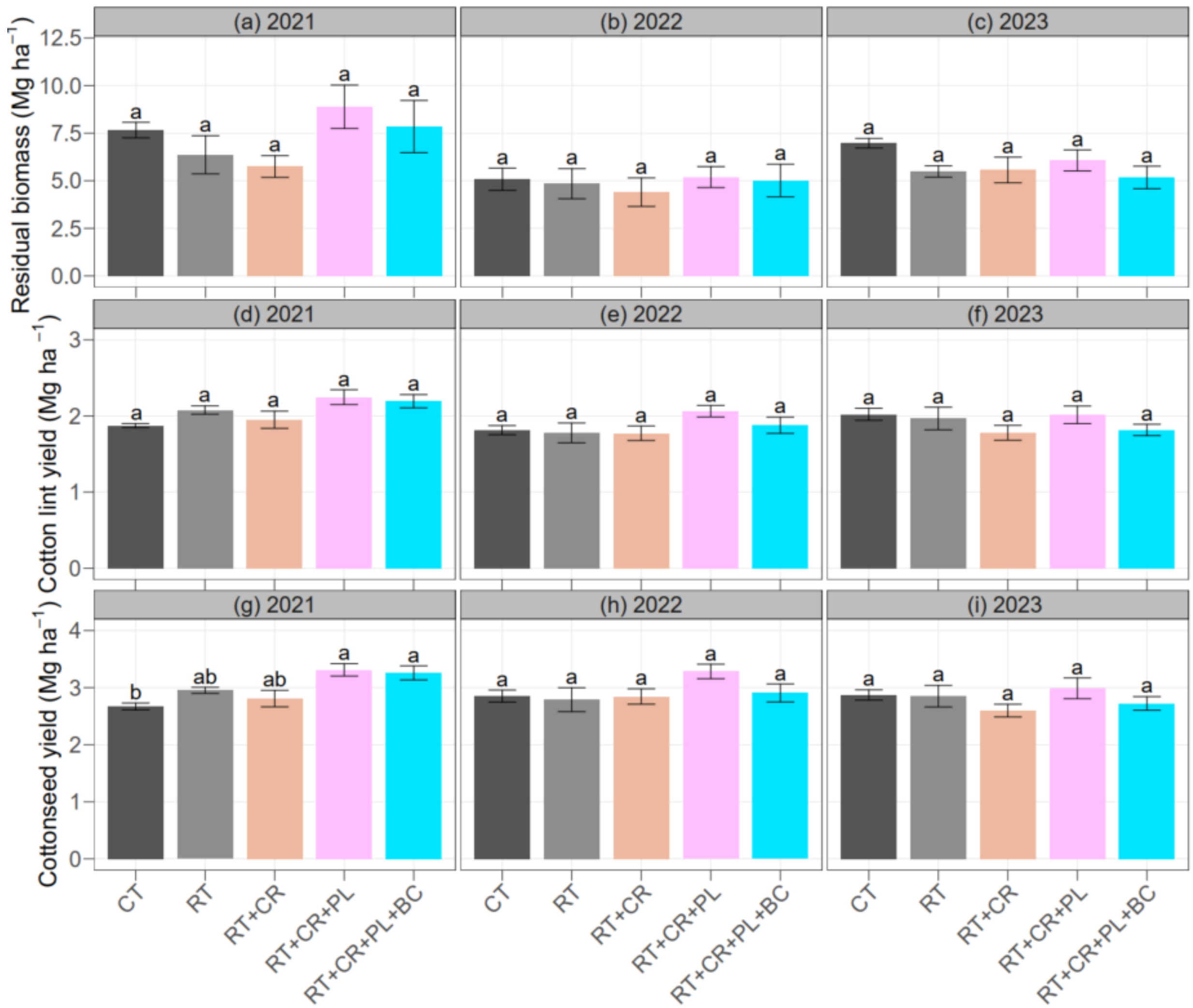

Figure 4.2. Impact of management systems on cotton biomass and yield in 2021, 2022, and 2023. Within each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($P < 0.05$). Error bars represent standard errors of the mean ($n = 4$). CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

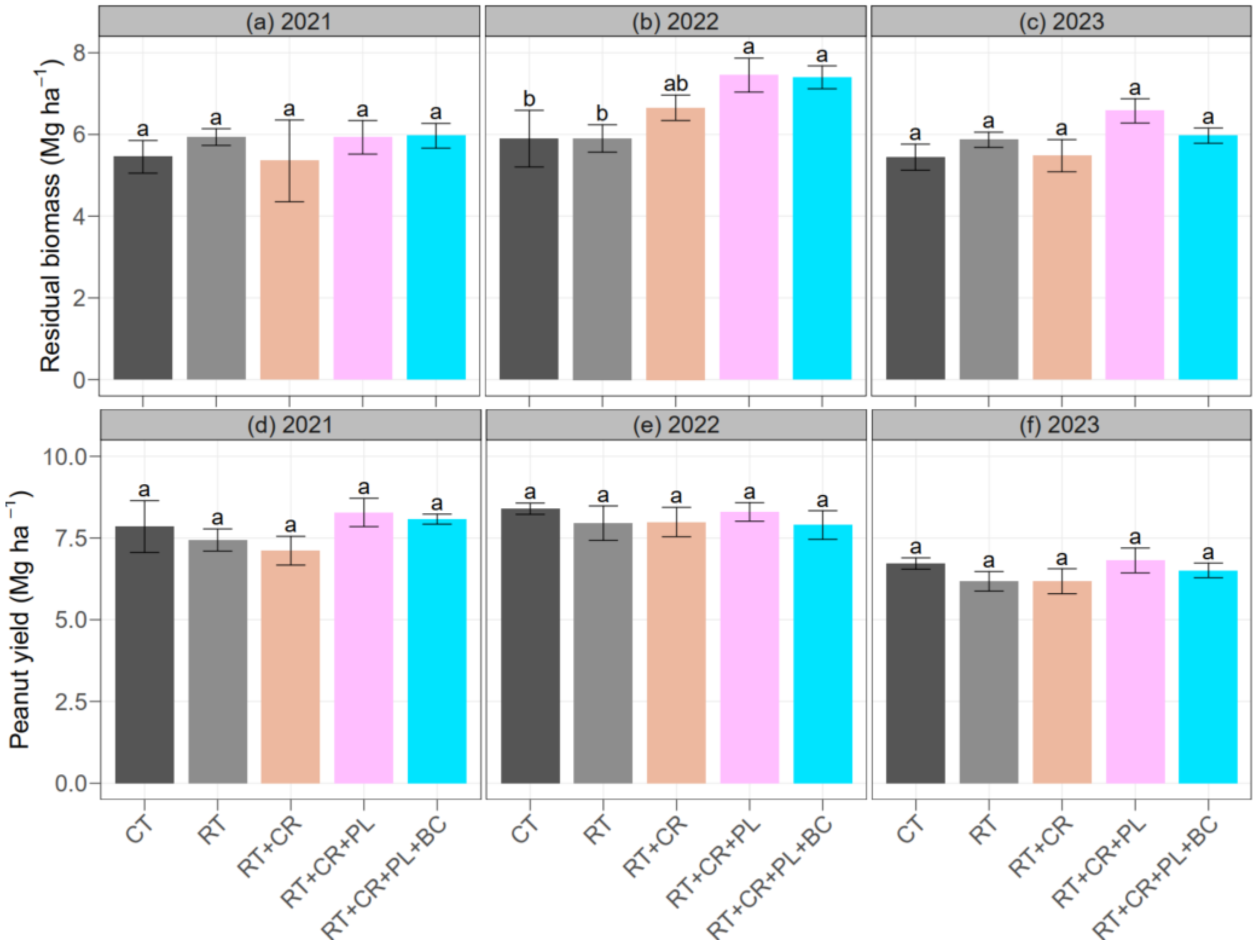

Figure 4.3. Impact of management systems on peanut biomass and yield in 2021, 2022, and 2023. Within each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($P < 0.05$). Error bars represent standard errors of the mean (n = 4). CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

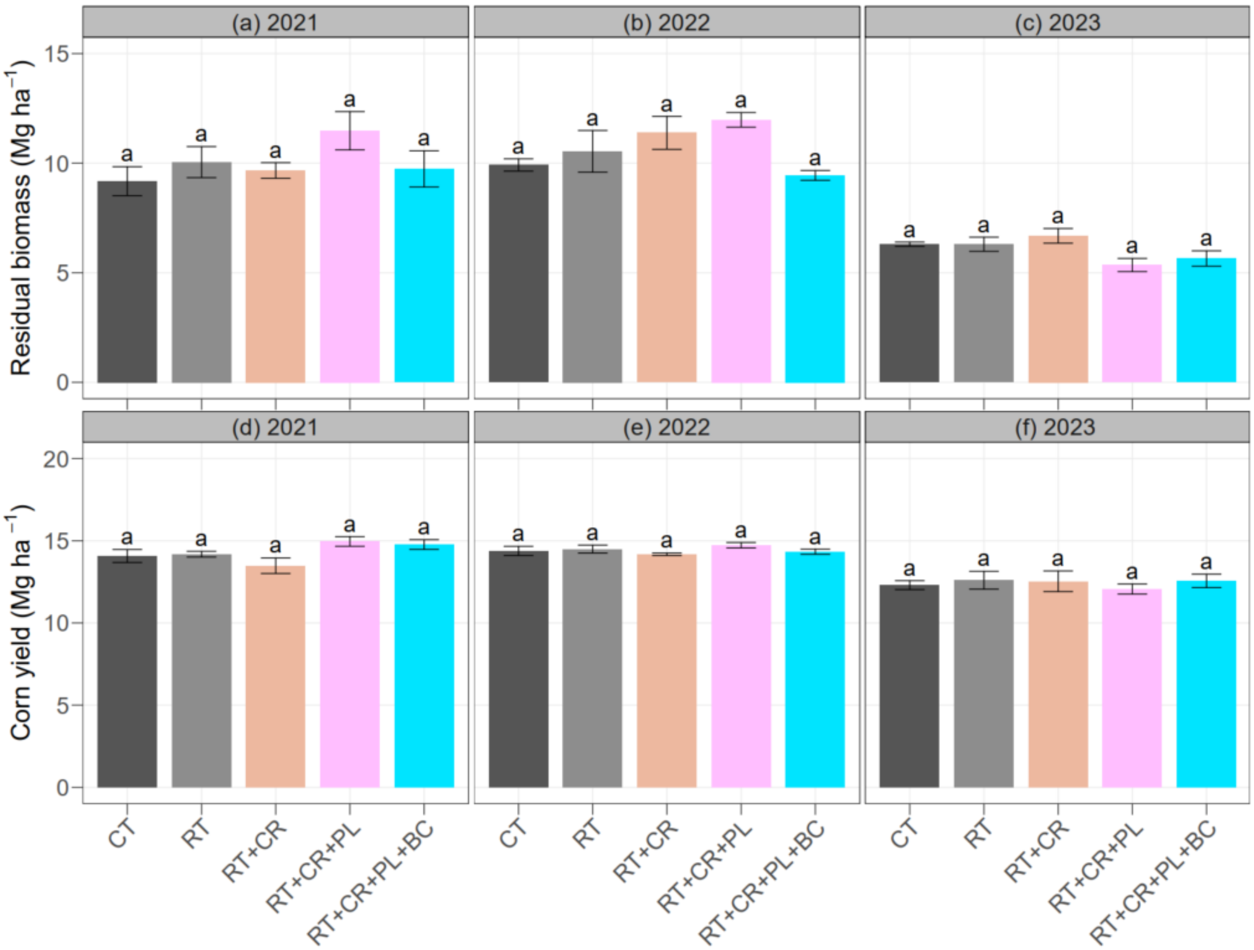

Figure 4.4. Impact of management systems on corn biomass and yield. Within each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($P < 0.05$). Error bars represent standard errors of the mean (n = 4). CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Supplemental Tables

Table S4.1: Nutrient composition (dry basis) of organic amendments used in the study.

Organic amendment	Total C	Total N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
	---------- $g\ kg^{-1}$ ----------											
	---------- 2021 ----------											
Poultry litter	NA	15.5	7.3	22.9	3.96	13.5	3.44	0.07	0.22	0.3	0.3	0.45
Biochar	866	2.95	1.77	4.88	3.45	24	0.37	0.25	0.25	0.49	0.86	0.25
	---------- 2022 ----------											
Poultry litter	275	39.1	16.8	39.9	9.2	34.8	15.8	0.12	0.55	0.37	4.46	0.49
Biochar	866	2.95	1.77	4.88	3.45	24	0.37	0.25	0.25	0.49	0.86	0.25
	---------- 2023 ----------											
Poultry litter	311	43.1	41.8	48.3	9.06	33.8	14.2	0.14	0.41	0.32	2.43	0.41
Biochar	712	2.32	5.4	5.56	3.93	30.5	0.35	0.17	0.17	0.35	3.07	0.17

Table S4.2: Field operation dates for corn, cotton, and peanut for the duration of the study.

Field operations	Corn			Cotton			Peanut		
	2020/2021	2021/2022	2022/2023	2020/2021	2021/2022	2022/2023	2020/2021	2021/2022	2022/2023
Cover crop planting	Nov. 9, 2020	Nov. 15, 2021	Nov. 10, 2022	Nov. 9, 2020	Nov. 15, 2021	Nov. 10, 2022	Nov. 9, 2020	Nov. 15, 2021	Nov. 10, 2022
Cover crop terminating	Mar. 24, 2021	Apr. 5, 2022	Mar. 15, 2023	Apr. 14, 2021	Apr. 26, 2022	Apr. 24, 2023	Apr. 14, 2021	Apr. 26, 2022	Apr. 24, 2023
Amendment application	Mar. 19, 2021	Mar. 15, 2022	Mar. 9, 2023	Apr. 1, 2021	May 11, 2022	May 9, 2023	Apr. 1, 2021	May 11, 2022	May 9, 2023
Tillage	April 7, 2021	Mar. 25, 2022	April 6, 2023	April 29, 2021	May 12, 2022	May 12, 2023	Apr. 29, 2021	May 12, 2022	May 12, 2023
Cash crop planting	Apr. 8, 2021	Apr. 22, 2022	Apr. 21, 2023	May 7, 2021	May 19, 2022	May 22, 2023	May 8, 2021	May 17, 2022	May 22, 2023
Plant sampling	Sept. 8, 2021	Aug. 10, 2022	Sept. 5, 2023	Oct. 11, 2021	Sept. 27, 2022	Oct. 10, 2023	Oct. 11, 2021	Sept. 27, 2022	Oct. 10, 2023
Harvesting	Sept. 23, 2021	Sept. 8, 2022	Sept. 6, 2023	Oct. 22, 2021	Nov. 2, 2022	Nov. 14, 2023	Oct. 22, 2021	Nov. 2, 2022	Oct. 27, 2023

Table S4.3: Inorganic fertilizer rates and sources applied in the corn study in 2021, 2022, and 2023.

Nutrients	Rates (kg ha^{-1})			Nutrient sources
	CT, RT, and RT+CR	RT+CR+PL	RT+CR+PL+BC	
2021				
N	304	304	304	Diammonium phosphate; Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
P_2O_5	108	108	108	Diammonium phosphate
K_2O	202	202	202	Potassium chloride
S	13	13	13	Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
2022				
N	356	356	356	Diammonium phosphate; Ammonium polyphosphate; Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
P_2O_5	75	75	75	Diammonium phosphate; Ammonium polyphosphate
K_2O	185	185	185	Potassium chloride
S	21	21	21	Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)

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Table S4.3 continued…

Nutrients	Rates (kg ha^{-1})			Nutrient sources
	CT, RT, and RT+CR	RT+CR+PL	RT+CR+PL+BC	
2023				
N	280	168	224	Urea, Urea ammonium nitrate solution, Diammonium phosphate, Ammonium sulfate
P_2O_5	115	-	58	Diammonium phosphate
K_2O	168	-	84	Potassium chloride
S	11	-	-	Ammonium sulfate

Notes: In 2021 and 2022, all plots received the same amount of inorganic fertilizer. The full rates of P, K, and S were applied at pre-planting in 2021 and 2022 and at the V3 stage (three-leaf collar) in 2023. In 2021, 14%, 47%, and 39% of N was applied at the pre-plant, V3, and V6 stages, respectively. 16%, 42%, and 42% of the N was applied at the pre-plant, V4, and V6 stages, respectively, in 2022. In 2023, the initial (V3) percentage of N applied was 60% for CT, RT, and RT+CR, 33% for RT+CR+PL, and 50% for RT+CR+PL+BC. The remaining amount of N was applied at the V6 stage: 40% for CT, RT, and RT+CR; 67% for RT+CR+PL; 50% for RT+CR+PL+BC.

CT, Conventional tillage; RT, Reduced tillage; RT+CR, Reduced tillage with cereal rye; RT+CR+PL, Reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, Reduced tillage with cereal rye, poultry litter, and biochar.

Table S4.4: Inorganic fertilizer rates and sources applied in the cotton study in 2021, 2022, and 2023.

Nutrients	Rates (kg ha^{-1})			Nutrient sources
	CT, RT, and RT+CR	RT+CR+PL	RT+CR+PL+BC	
2021				
N	101	101	101	Super Rainbow Homogenized (28-0-0-5S); Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
P_2O_5	79	79	79	Triple super phosphate
K_2O	110	110	110	Potassium chloride
S	5	5	5	Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
B	0.6	0.6	0.6	Borosol
2022				
N	133	133	133	Diammonium phosphate; Ammonium sulfate; Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
P_2O_5	52	52	52	Diammonium phosphate
K_2O	101	101	101	Potassium chloride
S	10	10	10	Ammonium sulfate; Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
B	0.6	0.6	0.6	Borosol

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Table S4.4 continued…

Nutrients	Rates (kg ha^{-1})			Nutrient sources
	CT, RT, and RT+CR	RT+CR+PL	RT+CR+PL+BC	
2023				
N	84	-	28	Urea, Diammonium phosphate
P_2O_5	45	-	-	Diammonium phosphate
K_2O	78	-	-	Potassium chloride, Potassium sulfate
S	11	-	-	Potassium sulfate
B	0.6	-	-	Fertilizer Borate

Notes: In 2021 and 2022, all plots received the same amount of inorganic fertilizer. The full rates of P, K, S, and B were applied at pre-plant or early vegetative stage in all years. In 2023, the RT+CR+PL received no inorganic fertilizer. 12% and 88% of N was applied at the early vegetative stage and square stage, respectively, in 2021. In 2022, 33% of N was applied at pre-plant and 67% at the square stage. In 2023, the percentage of N applied at the early vegetative stage was 67% for CT, RT, and RT+CR. The remaining amount of N (33%) for the CT, RT, and RT+CR was applied at the square stage. All the N for the RT+CR+PL+BC was applied at the square stage.

CT, Conventional tillage; RT, Reduced tillage; RT+CR, Reduced tillage with cereal rye; RT+CR+PL, Reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, Reduced tillage with cereal rye, poultry litter, and biochar.

Table S4.5: The *p*-values of the effects of the management systems on corn, cotton, and peanut biomass and yield.

Management effect	Cotton			Peanut		Corn	
	Biomass	Lint yield	Cottonseed	Biomass	Yield	Biomass	Yield
2021	0.246	0.061	**0.005**	0.906	0.314	0.204	0.100
2022	0.798	0.121	0.123	**0.027**	0.804	0.063	0.586
2023	0.220	0.427	0.437	0.091	0.210	0.062	0.958

Note: *p*-values in bold text indicate significant effect terms ($P < 0.05$).

Table S4.6: The *p*-values of the effects of the management systems on cotton fiber quality indicators.

Management effect	Fiber length	Fiber strength	Micronaire	Uniformity	Rd	+b
2021	0.672	0.777	0.123	0.986	0.752	0.798
2022	0.955	0.105	0.801	0.250	0.962	**0.014**
2023	0.297	0.776	0.992	0.221	0.452	0.770

Note: *p*-values in bold text indicate significant effect terms ($P < 0.05$).
Rd, fiber reflectance; +b, fiber yellowness.

Table S4.7: The *p*-values of the effects of the management systems on physical quality indicators of peanut kernel.

Management effect	SMK	SS	TSMK	OK
2021	0.433	0.712	0.464	0.839
2022	0.454	0.897	0.160	0.134
2023	0.785	0.157	0.807	0.425

Note: *p*-values in bold text indicate significant effect terms ($P < 0.05$).
SMK, sound mature kernels; SS, sound split; TSMK, total sound mature kernels; OK, other kernels.

Table S4.8: The *p*-values of the effects of the management systems on protein and nutrient content of corn seed, peanut seed, and hull.

Management Effect	Protein	P	K	Mg	Ca	S	Zn	Mn	Fe	Cu	Mo
	-- Protein and nutrient content of peanut seed --										
2022	0.569	0.156	0.251	0.758	0.837	0.102	0.068	0.592	0.990	0.074	0.061
2023	0.871	1.000	0.422	0.432	0.639	0.972	0.390	0.221	0.143	**0.018**	**<0.001**
	-- Protein and nutrient content of peanut hull --										
2022	0.059	0.649	0.992	0.872	0.888	0.903	0.451	0.057	0.496	0.059	**<0.001**
2023	0.673	0.782	0.553	0.528	0.482	0.620	0.731	0.648	0.713	0.115	**0.011**
	-- Protein and nutrient content corn of c seed --										
2021	0.600	0.463	0.417	0.393	0.421	0.651	0.423	0.452	0.184	0.861	0.451
2022	0.284	0.534	0.778	0.885	0.250	0.684	0.753	0.160	0.920	0.267	0.121
2023	0.879	0.107	0.119	0.218	0.141	0.055	0.184	**0.027**	0.233	**0.048**	**<0.001**

Note: *p*-values in bold text indicate significant effect terms ($P < 0.05$).

Table S4.9: The *p*-values of the effects of the management systems on corn, cotton, and peanut biomass nutrient uptake.

Management effect	C	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
	---------- Cotton biomass nutrient uptake ----------												
2021	0.228	0.209	0.394	0.145	0.145	0.375	0.313	0.355	0.105	0.503	0.163	**0.032**	0.168
2022	0.694	0.571	0.260	0.596	0.755	0.645	0.583	0.758	0.507	0.177	0.659	0.327	0.364
2023	0.170	0.396	0.702	0.684	0.232	0.581	0.639	0.678	0.769	0.931	0.963	0.541	0.653
	---------- Peanut biomass nutrient uptake ----------												
2021	0.909	0.886	0.787	**0.040**	0.520	0.859	0.842	0.821	0.847	**0.031**	0.784	0.069	**0.005**
2022	**0.022**	0.183	**0.041**	**0.015**	**0.013**	0.082	0.306	**0.008**	**0.066**	0.383	0.383	0.079	**<0.001**
2023	0.125	0.100	**0.009**	**0.022**	**0.021**	0.925	0.673	0.212	**0.001**	0.233	0.591	0.603	**<0.001**
	---------- Corn biomass nutrient uptake ----------												
2021	0.194	0.327	0.168	0.427	0.603	0.748	0.275	0.647	0.991	0.864	0.426	0.053	**0.001**
2022	0.218	0.347	**0.005**	**0.004**	**0.003**	0.070	0.173	0.748	0.317	**0.020**	0.484	0.516	**<0.001**
2023	0.068	0.801	0.149	0.127	0.095	0.694	**0.004**	0.144	**0.020**	**0.031**	0.136	0.074	0.141

Note: *p*-values in bold text indicate significant effect terms ($P < 0.05$).

CHAPTER 5

COMPLEMENTARY EFFECTS OF REDUCED TILLAGE, CEREAL RYE, AND ORGANIC AMENDMENTS ON SOIL HEALTH IN ROW CROP PRODUCTION SYSTEMS

Ankomah, G., Habteselassie, M. Y., & Sintim, H. Y. (2025). Complementary effects of reduced tillage, cereal rye, and organic amendments on soil health in a row crop production system.

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Abstract

Integrating regenerative agricultural practices can foster complementary benefits and improve soil health. Field experiments were conducted from 2021 to 2024 on a Dothan sandy loam to evaluate the complementary effects of regenerative agricultural practices on soil health in row crop production systems. The management systems comprised conventional tillage (CT; control), reduced tillage (RT), reduced tillage with cereal rye (*Secale cereale;* RT+CR), reduced tillage with cereal rye and poultry litter (RT+CR+PL), reduced tillage with cereal rye, poultry litter, and biochar (RT+CR+PL+BC). The row crops were corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and peanut (Arachis hypogaea L.). The field was divided into three sections with each section having all crops appearing in rotation (corn-peanut-cotton sequence, peanut-cotton-corn sequence, and cotton-corn-peanut sequence). The CR was planted at a rate of 56 kg ha^{-1}, and the PL was applied at a rate of 4.48 Mg ha^{-1} in the RT+CR+PL plots. The RT+CR+PL+BC received 2.24 Mg ha^{-1} each of PL and BC. Soil health assessments were conducted in the spring of 2022, 2023, and 2024. The management systems had no impact on the physical properties except the soil resistance to penetration (SRP). Where there were significant differences, the SRP tended to be lower in the CT and/or RT compared to the RT+CR, RT+CR+PL, and RT+CR+PL+BC. The addition of PL in RT and CR tended to increase the concentrations of Mehlich-I extractable P, Zn, Mn, and Cu. Integrating RT, CR, PL, and BC showed no substantial benefits to overall soil health.

5.1. Introduction

The climatic conditions of the Southeastern United States favor the production of cotton (*Gossypium hirsutum* L.), peanut (Arachis hypogaea L.), and corn (*Zea mays* L.). The Southeastern states are the largest producers of cotton and peanut in the USA (Bukowski and Ates, 2023; USDA-ERS, 2025). The state of Georgia is the largest producer of peanut, accounting for about 40-55% of peanut production in the USA (Monfort et al., 2022). Also, Georgia is the second-largest producer of cotton (Hand et al., 2023). The climate of most of the southeastern region is characterized as humid subtropical, with a long summer, which is suitable for the production of cotton, peanut, and corn (Konrad et al., 2013). However, the warm temperatures, as well as intensive rainfall, result in the washing away of topsoil, rapid weathering of primary minerals, and depletion of mineral-derived plant nutrients in most of the regions (Nunes et al., 2019; Pincus et al., 2017).

Conservation tillage, cover crops, and organic amendments are key management practices implemented in the Southeastern US to improve soil health and ensure sustainable cotton, peanut, and corn production. The benefits of these management practices have been well documented (Adeli et al., 2019, 2022, 2024; Ankomah et al., 2024; Farmaha et al., 2022; Franklin and Bergtold, 2020; Franzluebbers, 2021; Mitchell et al., 2017; Sainju et al., 2006, 2007). Conservation tillage systems minimize soil erosion and improve soil physical properties (Franklin and Bergtold, 2020). Also, conservation tillage improves soil chemical and biological properties (Agyei et al., 2024; Mitchell et al., 2017; Nunes et al., 2020). In the state of Georgia, the common form of conservation tillage is strip tillage, where only the plant rows are tilled. Strip tillage is employed on about 50% of Georgia cotton acreage (Hand et al., 2023). A study conducted by Ankomah et al. (2024) indicated that strip tillage was as effective as conventional tillage in seedbed preparation for cotton production. Despite the benefits of strip tillage, there is less plant cover post-harvest, especially in the cotton and peanut phases. Including cover crops could potentially increase the percentage of plant cover and minimize nutrient losses post-harvest (Nyakatawa et al., 2001a; Franklin and Bergtold, 2020).

Cereal rye is one of the common cover crops grown in the Southeastern US and the USA at large due to its winter hardiness and high biomass production (Huddell et al., 2024). The high biomass accumulation of cereal rye could help suppress weeds in strip tillage systems and build soil carbon (Silva and Bagavathiannan, 2023; Sainju et al., 2007). Also, cereal rye minimizes nutrient losses, particularly during the winter months (Endale et al., 2010; Fageria et al., 2005). Despite the numerous benefits, cereal rye could have a high C/N ratio when terminated late (Otte et al., 2019). Otte et al. (2019) reported that the C/N ratio was 35 and 48 in the first and second years, respectively, when cereal rye was terminated late. The high C/N ratio of cereal rye could be desirable from a soil health perspective, as there will be slow release of N and build-up of soil organic matter (Otte et al., 2019; Pinnamaneni et al., 2022). However, during the early crop growing season, less amount of N may be mineralized to synchronize with crop demand. This is more problematic when cereal rye is planted after corn (Preza-Fontes et al., 2022). Corn produces high biomass and could have a high C/N ratio at harvest, which can exacerbate the N immobilization (Burgess et al., 2002).

Including poultry litter in a cereal rye and conservation tillage system could help improve nutrient cycling. Poultry litter contains nutrients and microbes that can potentially help in the mineralization of cereal rye and the release of nutrients during the active crop season (Chastain et al., 2010; Ankomah et al., 2024; Habteselassie et al., 2022). Studies have reported enriched soil nutrients with the application of poultry litter (Endale et al., 2010; Mitchell and Tu, 2006; Nyakatawa et al., 2001). Despite the soil nutrient enrichment benefits derived from poultry litter**,** surface application in conservation tillage systems is prone to nutrient losses (Endale et al., 2010). Applying biochar with poultry litter can reduce nutrient losses and enhance soil carbon accumulation (Adeli et al., 2022; Agegnehu et al., 2015). Studies have substantiated that applying biochar produced from crop residues and wood builds soil organic matter and enhances soil nutrient retention (Agegnehu et al., 2015; Giannetta et al., 2023; Kabir et al., 2023). The enhanced soil nutrient retention has been attributed to the large surface area, porous structure, and high cation exchange capacity of biochar (Allohverdi et al., 2021; Kabir et al., 2023).

Due to the limitations of each management practice, integrating them could help complement each other and improve soil health. The hypothesis was that: (1) the high biomass produced by cereal rye will minimize nutrient losses and build soil organic matter in reduced tillage system but late termination could lead to nutrient immobilization, (2) including poultry litter in reduced tillage and cereal rye system will enhance nutrient cycling but surface application of poultry litter will increase nutrient losses, and (3) further adding biochar would enhance nutrient retention, minimize nutrient losses, and build soil organic matter. The research objective was to evaluate the complementary effect of reduced tillage, cereal rye, poultry litter, and biochar on soil health in row crop production systems.

5.2. Materials and Methods

5.2.1. Experimental site

The experiment was conducted from 2021 to 2024 on a Dothan sandy loam (Fine-loamy, kaolinitic, thermic Plinthic Kandiudults) at the Southeast Georgia Research and Education Center, Midville, GA (32°52'46.44" N, 82°12'33.86" W). The soil at a depth of 0-15 cm contained 93.3% sand, 0.20% silt, and 6.5% clay. Over the long term (1958-2016), the average air temperature was 18 °C, with an annual precipitation of 1147 mm (AEMN, 2025). The monthly average temperature and monthly precipitation are shown in Table 5.1. The annual average temperatures were 18.5 °C, 18.8 °C, 19.1 °C, and 19.5 °C in 2021, 2022, 2023, and 2024, respectively. The annual precipitation was 1110 mm, 1003 mm, 1354 mm, and 1655 mm in 2021, 2022, 2023, and 2024, respectively.

5.2.2. Field experiment

Field experiments were established to evaluate the impacts of regenerative agricultural practices on soil health in row crop production systems. The management systems comprised conventional tillage (CT; control), reduced tillage (RT), reduced tillage with cereal rye (RT+CR), reduced tillage with cereal rye and poultry (broiler) litter (RT+CR+PL), and reduced tillage with cereal rye, poultry litter, and biochar (RT+CR+PL+BC). The experimental plot size was 7.3 m by 9.1 and the design utilized was a randomized complete block design with four replications. Cereal rye was planted in the fall with a John Deere 750 no-till drill at a seeding rate of 56 kg ha^{-1} and terminated in the spring with glyphosate [isopropylamine salt of N-(phosphonomethyl) glycine].

Tillage operations were done in the spring of each year before planting the crops. The CT plots were prepared by tilling with a KMC tillovator (Kelly Manufacturing Co., South Dillon, SC) to a depth of 41 cm. Only the plant rows were tilled for the RT, RT+CR, RT+CR+PL, RT+CR+PL+BC plots, using a KMC strip-till implement (Kelly Manufacturing Co., South Dillon, SC). The poultry litter was obtained from Powell Poultry Farms, LLC, Omega, GA, and was applied in the RT+CR+PL plots at a rate of 4.48 Mg ha^{-1}. The RT+CR+PL+BC plots received 2.24 Mg ha^{-1} each of poultry litter and biochar. Pinewood waste was used in producing the biochar and was obtained from Wakefield BioChar, based in Valdosta, GA. Wakefield BioChar produces the biochar at a pyrolysis temperature of 600 °C. Table S5.1 contains the nutrient composition of the poultry litter and biochar. Tillage operation and organic amendment application dates are presented in Table S5.2.

The field was divided into three sections to enable the annual evaluation of the impacts of the management systems on soil health in all the row crops. In the first section, corn, peanut, and cotton were planted in 2021, 2022, and 2023 (corn-peanut-cotton sequence), respectively. In the second section, peanut were planted in 2021, followed by cotton in 2022 and corn in 2023 (peanut-cotton-corn sequence). In the third section, cotton, corn, and peanut were planted in 2021, 2022, and 2023, respectively (cotton-corn-peanut sequence). Each year, corn was planted in April while cotton and peanut were planted in May. Each year, planting was not done into the standing stubble or stalks of the previous crop to minimize obstruction and enhance germination. During the 2021 and 2022 seasons, all plots in the corn and cotton phases received the same inorganic fertilizer. In the 2023 season, the CT, RT, and RT+CR plots received the full recommended rate of inorganic fertilizer, while the RT+CR+PL and RT+CR+PL+BC plots received a reduced amount after adjusting for the nutrients estimated to be available from the poultry litter. It was estimated that 60% of the N, 80% of P, K, and S in poultry litter would be available (Bryant et al., 2020). Tables S5.3 and S5.4 contain the inorganic fertilizer sources and rates applied. No inorganic fertilizers were applied for the peanut phase in all years. Weed and insect pest, and disease control followed recommendations in the production guide for the row crops developed by the University of Georgia Cooperative Extension (Bryant et al., 2020; Hand et al., 2021; Monfort et al., 2022).

5.2.3. Data collection

5.2.3.1. Initial soil analysis

Initial soil samples were collected at the block level from 0-15 and 15-30 cm soil depths in fall 2020, before establishing the study in 2021. The samples were air-dried and ground to pass through a 2-mm sieve for chemical and nutrient analyses. Organic matter was determined using the loss on ignition method (Crouse et al., 2014), while soil pH was measured with a pH meter

(PC 9500, Apera Instruments) in a 1:2 soil-to-water ratio (Crouse et al. 2014). Available soil nutrients including phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), boron (B), zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu) were extracted using the Mehlich-I procedure (Crouse et al., 2014) and analyzed with an inductively coupled plasma optical emission spectrophotometer (PerkinElmer® Avio 200 Cross-Flow ICP-OES). The initial soil properties are shown in Table 5.2.

5.2.3.2. Soil health assessments

Soil health assessments were conducted in the spring of 2022, 2023, and 2024 (Table S5.2). Soil resistance to penetration, water infiltration, and soil samples were collected before terminating the CR and undertaking tillage operations. Soil resistance to penetration (SRP) was measured using a penetrometer, positioned 15 cm from the plant rows and within the 0-30 cm soil depth at 5 cm intervals, with four insertions per plot (FieldScout SC 900 Meter, Spectrum Technologies, Aurora, IL, USA). Water infiltration was measured using a double-ring infiltrometer (Turf-Tech International, Tallahassee, FL, USA) at three positions per plot. Bulk density at depths of 0-15 cm and 15-30 cm was determined using a 5.08 cm bulk density sampling kit (AMS Inc., American Falls, ID). In 2023, we measured bulk density only after cotton due to experimental limitations. Volumetric water content (VWC) was estimated based on the bulk density. Composite soil samples were collected from 0-15 cm and 15-30 cm depths, air-dried, ground, and sifted with a 2-mm sieve for chemical and nutrient analyses. Soil respiration, organic matter, soil pH, and available nutrients were measured following procedures as previously described (Crouse et al., 2014).

5.2.4. Statistical analyses

Separate statistical analyses were performed for each section of the field because of the differences in the crop sequence (corn-peanut-cotton, peanut-cotton-corn, cotton-corn-peanut). The soil health parameters for each section of the field were analyzed as a repeated measure with a linear mixed model using the “lme4" package in R (Bates et al., 2015) For the SRP, bulk density, VWC, soil respiration, organic matter, pH, and nutrients, the soil depth and year were assigned as within-plot factor variables, the management systems as between-plot factor variables, and the block was a random term. Similarly, for the water infiltration, organic matter ratios, and soil nutrient ratios, year was designated as a within-plot factor variable, the management systems as between-plot factor variables, and the block was a random term. The assumptions of normality of residuals, homoscedasticity of variance, and sphericity were tested. Where necessary, suitable transformations (Box-Cox, square root, and inverse transformation methods) and corrections (Greenhouse–Geisser and Huynh–Feldt correction methods) were applied. Mean separations were performed using least square means and the Sidak comparison procedure, implemented with the ‘emmeans’ package in R (Lenth et al., 2025).

5.3. Results

5.3.1. Soil physical indicators

The main effects of the management systems were not significant on the SRP at the various soil depths in the corn-peanut-cotton and peanut-cotton-corn sequences (Table S5.5). Significant differences were observed in the SRP in the cotton-corn-peanut sequence. The SRP varied significantly by depth and year in all years. Also, there were some significant management, depth, and year interaction effects on the SRP (Table S5.5). Generally, when averaged across all the management systems, the SRP increased with depth. Also, except for a few instances, all the management systems showed compaction beyond the 15 cm soil depth in all crop sequences (Table S5.6, S5.7, and S5.8; Figures 5.1, 5.2, 5.3). Values greater than 2 MPa indicate the soil is compacted and root growth may be restricted (Duiker, 2002; Moebius-Clune et al., 2016; Ankomah et al., 2024). Despite no significant differences in the SRP between the management systems, when measurements were done in 2022 after corn (corn-peanut-cotton sequence), the CT and RT showed less compaction at the 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, and 30 cm depths compared to the RT+CR, RT+CR+PL, and RT+CR+PL+BC (Table S5.6; Figure 5.1a). Similarly, in the cotton-corn-peanut sequence, when measurements were done in 2022, after cotton, the CT and RT showed less compaction at the various soil depths compared to the RT+CR, RT+CR+PL, and RT+CR+PL+BC, but the differences were not always significant. Also in 2022, after cotton and in 2023 after corn, the RT+CR+PL tended to consistently have higher SRP values at the various soil depths compared to other management systems (Table S5.8; Figure 5.3a).

Additionally, in 2024, after peanut at the 25 cm and 30 cm depths, the CT had lower SRP values than the other management systems, but the differences were not consistently significant. The SRP values for the CT were only significantly lower than the RT+CR+PL (Table S5.8).

The main effects of management systems and the interaction effects of management systems and year interaction were not significant on water infiltration across all crop sequences (Table S5.5). However, the water infiltration varied by year in all the crop sequences. On average, the water infiltration was higher when measurements were done in 2023 and 2022 after peanut in the corn-peanut-cotton and peanut-cotton-corn sequences, respectively (Table 5.3). When averaged across the management systems, the water infiltration in the cotton-corn-peanut sequence was higher when measurements were done in 2022 after cotton. The management systems had no significant effect on the bulk density and VWC in all the crop sequences (Table S5.5). When averaged across the management systems, the bulk density tended to be higher within the 15-30 cm soil depth in all years in the peanut-cotton-corn sequence, in 2024 after cotton (corn-peanut-cotton sequence), and after peanut (cotton-corn-peanut sequence; Table 5.4). The VWC for all the management systems was low (less than 0.15 cm^3 cm^{-3}) in the peanut-cotton-corn and cotton-corn-peanut sequences (Table 5.5).

5.3.2. Soil respiration and organic matter

The main effects of management systems were not significant on soil respiration and organic matter (Table S5.5). However, the soil respiration varied significantly by depth and year in the corn-peanut-cotton and cotton-corn-peanut sequences, and by depth only in the peanut-cotton-corn sequence. Additionally, the organic matter changed significantly by depth and year in the peanut-cotton-corn sequence and by depth only in the corn-peanut-cotton and cotton-corn-peanut sequences (Table S5.5). Overall, when averaged across all the management systems, the soil respiration and organic matter were higher in the 0-15 cm depth compared to the 15-30 cm depth (Table 5.6, 5.7). In the corn-peanut-cotton sequence, when averaged across the management systems, the soil respiration within the 0-15 cm depth tended to be higher after peanut in 2023, while the organic matter within the 0-15 cm depth tended to be higher in 2024 after cotton. Similarly, in the peanut-cotton-corn sequence, when averaged across the management systems, the soil respiration within the 0-15 cm depth tended to be higher after peanut in 2022, while the organic matter within the 0-15 cm tended to be higher after corn in 2024 (Table 5.6, 5.7). In the cotton-corn-peanut sequence, the soil respiration within the 0-15 cm depth tended to be higher after cotton in 2022, and the organic matter within the 0-15 cm depth tended to be higher after corn in 2023 (Table 5.6, 5.7). The organic matter content of the 0-15 cm depth was divided by the 15-30 cm depth to determine stratification ratios (Table S5.9). There was no indication of significant organic matter stratification within the 0-15 cm and 15-30 cm soil depths between the management systems in all the crop sequences (Table S5.10, S5.11, S5.12).

5.3.3. Soil pH and nutrients

The management systems had a significant effect on the soil pH in only the cotton-corn-peanut sequence (Table S5.5). In 2024, after peanut, the pH within the 0-15 cm depth for the CT was significantly higher than the RT and RT+CR but not the RT+CR+PL and RT+CR+PL+BC (Table 5.10). In general, when averaged across all the management systems, the soil pH was higher within the 0-15 cm compared to the 15-30 cm in all crop sequences (Table S5.5, Table 5.8, 5.9, and 5.10). The main effects of the management systems were significant on soil nutrients in only a few instances in all the crop sequences (Table S5.5). In the corn-peanut-cotton sequence, the management systems had a significant effect on the P, Zn, Mn, and Cu. In the peanut-cotton-corn sequence, the Mg and Cu were significantly affected by the management systems. In the cotton-corn-peanut sequence, the management systems had a significant effect on the Zn and Cu. All the soil nutrients varied significantly by depth except B in the corn-peanut-cotton sequence; except K, B, and Cu in the peanut-cotton-corn sequence; except K and Cu in the cotton-corn-peanut sequence (Table S5.5). Overall, when averaged across the management systems, the soil nutrients were higher in the 0-15 cm soil depth compared to the 15-30 cm (Tables 5.8, 5.9, and 5.10). Also, all the soil nutrients varied significantly by year except Mn and Fe in the corn-peanut-cotton sequence and K in the cotton-corn-peanut sequence (Table S5.5). Overall, when averaged across the management systems, the soil nutrients within 0-15 cm soil depth in all three crop sequences tended to be higher in 2024 (Tables 5.8, 5.9, and 5.10). The interaction effects of the management, depth, and year on the soil nutrients were only significant in a few instances (Table S5.5).

In the corn-peanut-cotton sequence, the P within the 0-15 cm soil depth in 2023 after peanut and 2024 after cotton was significantly higher in the RT+CR+PL plots compared to CT, RT, and RT+CR but not the RT+CR+PL+BC (Table 5.8). The P within the 0-15 cm soil depth for the

RT+CR+PL in 2023 after peanut was 66%, 71%, and 92% higher than the CT, RT, and RT+CR, respectively. In 2024, after cotton, the P within the 0-15 cm depth for the RT+CR+PL was 96%, 82%, and 99% higher than the CT, RT, and RT+CR, respectively. In addition, the P within the 0-15 cm soil depth for the RT+CR+PL+BC was higher compared to the CT, RT, and RT+CR, with significant differences observed in 2024 after cotton. The Zn within the 0-15 cm soil depth in 2023 after peanut and in 2024 after cotton, as well as the Mn within the 0-15 cm depth in 2024 after cotton, followed a similar trend as the P, but the differences were not always significant (Table 5.8). In 2023, after peanut, and in 2024, after cotton, the Zn within the 0-15 cm depth for the RT+CR+PL was significantly higher than the CT. Also, in 2024, after cotton, the Mn within the 0-15 cm depth for the RT+CR+PL+BC was significantly higher than the CT. Significant differences were observed in the Cu in all the crop sequences. The RT+CR+PL and RT+CR+PL+BC had higher Cu within the 0-15 cm and 15-30 cm depths in 2023 after peanut and within the 0-15 cm depth in 2022 after corn and in 2024 after cotton, but the differences were not consistently significant when compared to the other management systems (Table 5.8).

In the peanut-cotton-corn sequence, the CT and RT+CR+PL+BC had higher Mg within the 0-15 cm depth in 2022 after peanut (Table 5.9). The Cu within the 0-15 cm depth in 2022, after peanut, and in 2024, after corn, was higher for the RT+CR+PL and RT+CR+PL+BC compared to the CT, RT, and CR+RT. However, the Cu within the 0-15 cm depth in 2022 after peanut for the RT+CR+PL and RT+CR+PL+BC was not significantly higher than the RT (Table 5.9). Similarly, in the cotton-corn-peanut sequence, the Zn and Cu within the 0-15 cm depth in 2023 after corn and in 2024 after peanut were higher in the RT+CR+PL and RT+CR+PL+BC plots compared to the CT, RT, and RT+CR (Table 5.10). The differences were, however, not consistently significant. Additionally, despite no significant differences, the P within the 0-15 cm depth in 2022 after cotton, in 2023 after corn, and in 2024 after peanut were consistently higher in the RT+CR+PL and RT+CR+PL+BC plots compared to the CT, RT, and RT+CR (Table S5.5 and Table 5.10). After cotton in 2022, P within the 0-15 cm soil depth was higher by 19-42%. Following corn in 2023, the P within the 0-15 cm depth for the RT+CR+PL and RT+CR+PL+BC was 26-82%. Similarly, in 2024, after peanut, the P within the 0-15 cm soil depth for the RT+CR+PL and RT+CR+PL+BC was 53-108% higher than the CT, RT, and RT+CR.

The soil nutrients in the 0-15 cm depth were divided by those of the 15-30 cm depth to determine stratification ratios. The main effects of management systems were significant on the Cu ratios in all the crop sequences (Table S5.9). Also, in the peanut-cotton-corn sequence, the management system significantly affected the P and Ca stratification ratios (Table S5.9). In 2023, after cotton, and in 2024, after corn (peanut-cotton-corn sequence), the P was more accumulated within the 0-15 cm soil depth in the RT+CR+PL and RT+CR+PL+BC plots than in the CT, RT, and RT+CR (Table S5.11). However, in 2024, after corn, the P stratification ratio for the RT+CR+PL+BC was not statistically different from the CT, RT, and RT+CR. The Ca stratification ratio in 2024, after corn, followed a similar trend as the P ratio (Table S5.11). Overall, the Cu was stratified (accumulated) more in the 0-15 cm soil depth of the RT+CR+PL and RT+CR+PL+BC plots in all the crop sequences (Table S5.10, S5.11, and S5.12). In 2024, after cotton (corn-peanut-cotton sequence) and after corn (peanut-cotton-corn sequence), the RT+CR+PL and RT+CR+PL+BC had more Cu accumulated in the 0-15 cm soil depth compared to the CT, RT, and RT+CR (Table S5.10, S5.11). However, in 2024, after corn (peanut-cotton-corn sequence), the Cu stratification ratio for the RT+CR+PL+BC was not statistically different from the CT, RT, and RT+CR. Similarly, in 2023, after corn (cotton-corn-peanut sequence), the Cu was more stratified in the RT+CR+PL than in the CT and RT+CR (Table S5.12).

5.4. Discussion

Generally, when averaged across all the management systems, the SRP increased with depth. Also, except for a few instances, all the management systems showed compaction beyond the 15 cm soil depth in all crop sequences. The soil at the experimental site is characterized as Ultisol, which has sandy topsoil and clay at the sublayer (Swaby et al., 2016). Moreover, in most instances, the soil was not at field capacity at the time of taking the measurements (Table S5). The volumetric content within the 0-15 cm and 15-30 cm soil depths for the management systems was less than (less than 0.15 cm^3 cm^{-3}) in most cases. The soil at the study site is Dothan sandy loam and a study by Jabro et al. (2009) indicated that such a soil is expected to be at field capacity when the volumetric water content is 0.23 cm^3 cm^{-3}. It is worth mentioning that tillage operations may lead to changes in soil condition for the succeeding crops. Studies have reported the impact of soil moisture on SRP. Soil resistance to penetration decreased as water content increased near saturation (Lardy et al., 2022; Souza et al., 2021).

Where there were significant differences, the SRP tended to be lower in the CT and/or RT compared to the RT+CR, RT+CR+PL, and RT+CR+PL+BC. This could be attributed to the presence of CR in the RT+CR, RT+CR+PL, and RT+CR+PL+BC plots. Soil health assessments were conducted before terminating the CR, and the CR root matrix may have caused physical impedance (Ankomah et al., 2024). The minimal differences in the SRP and the lack of differences in water infiltration, bulk density, and VWC in all years could be due to the changing of planting rows every year. Planting was not done into the standing stubble or stalks of the previous crop. This was the practice at the research station to minimize obstruction during planting and to enhance germination. In a no-tillage system, previous crop residue has been indicated to cause poor plant establishment due to a lack of seedbed (Arvidsson et al., 2014). Generally, the bulk density was higher within the 15-30 cm soil depth which is supported by the SRP results.

Soil respiration and organic matter did not differ significantly by the management systems, but there were instances where they varied by year and depth. Soil respiration is an indicator of microbial activity (heterotrophic respiration) and the lack of differences suggest the various management systems resulted in similar microbial response. The management systems had similar organic matter levels which could explain the no differences in microbial activities. We expected including cereal rye, poultry litter, and biochar in reduced tillage system (RT+CR, RT+CR+PL, and RT+CR+PL) to build soil organic matter and subsequently increase micobial activities but was not evident in our study. The planting rate of cereal rye (56 kg ha^{-1}) and the biochar application rate (2.24 Mg ha^{-1}) in our study were relatively low compared to studies that observed an increase in soil organic matter (Pinnamaneni et al., 2022; Agegnehu et al., 2015). Pinnamaneni et al. (2022) planted rye at a seeding rate of 112 kg ha^{-1} while Agegnehu et al. (2015) applied bichar at a rate of 22.4 Mg ha^{-1}. As expected, when averaged across all the management systems, the soil respiration and organic matter within the 0-15 cm soil depth was higher than the 15-30 cm soil depth. This shows there is more food substrate for soil micoorganisms to utilize (USDA-NRCS, 2014). The less soil compaction within the 0-15 cm could also account for the higher soil respiration (Figure 1, 2, 3; Table 4). Soil compaction reduces soil porosity and results in limited oxygen for microbial activity (USDA-NRCS, 2014; Frene et al., 2024). There was no indication of significant organic matter stratification within the 0-15 cm and 15-30 cm soil when comparing the CT to the RT systems in all the crop sequences.

There was only one instance where differences were observed in the soil pH between the management systems. Where there was a difference, the PL plots (RT+CR+PL and RT+CR+PL+BC) had similar soil pH as the CT. Overall, the soil pH remained the same for all the management systems in all years. In general, the pH within the 0-15 cm soil depth for all the management systems in all crop sequences was near neutral or neutral (ranging from 6.85 to 7.38). Overall, the management systems had a little impact on the soil nutrients as there were a few instances where significant differences were observed. The previous crops potentially utilized most of the nutrients while some may have been lost during the winter months. There were instances where the plots that received PL (RT+CR+PL and RT+CR+PL+BC) showed higher P, Zn, Mn, and Cu within the 0-15 cm soil depth, but the differences were not always consistent. The high accumulation of these nutrients for the RT+CR+PL and RT+CR+PL+BC suggest there was carryover of some of the nutrients in the poultry litter to the following year. Other studies have reported higher concentrations of extractable P, Zn, Mn, and Cu with the application of PL (Endale et al., 2010; Mitchell and Tu, 2006; Tewolde et al., 2011). Overall, when averaged across the management systems, the soil nutrients within 0-15 cm soil depth in all three crop sequences were relatively higher in 2024, indicating the accumulation of nutrients over the study period.

5.5. Conclusions

Field experiments were conducted from 2021 to 2024 on a Dothan sandy loam to evaluate the complementary effect of RT, CR, PL, and BC on soil health in row crop systems. The management systems had no impact on the soil physical indicators except the SRP. Generally, when averaged across all the management systems, the SRP increased with depth. Also, in several instances all the management systems showed compaction beyond the 15 cm soil depth in all crop sequences which was explained by the VWC. The VWC was low (less than 0.15 cm^3 cm^{-3}) in most cases, indicating the soil was not at field capacity. Where there were significant differences, the SRP tended to be lower in the CT and/or RT compared to the RT+CR, RT+CR+PL, and RT+CR+PL+BC. Soil respiration and organic matter did not differ significantly by the management systems. When averaged across all the management systems, the soil respiration and soil organic matter was higher within the 0-15 cm soil depth which indicates more food substrate and microbial activity. The addition of PL in RT and CR tended to increase the concentrations of

Mehlich-I extractable P, Zn, Mn, and Cu. Integrating RT, CR, PL, and BC showed no substantial benefits to overall soil health.

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Tables

Table 5.1: Monthly average temperature and precipitation in Midville, GA, from 2021 to 2024.

Month	Mean temperature				Precipitation			
	2021	2022	2023	2024	2021	2022	2023	2024
	°C				mm			
January	9.0	8.2	11.0	9.1	131	96	191	55
February	10.1	12.2	15.0	11.7	163	49	83	132
March	15.4	15.7	15.6	15.7	118	76	78	187
April	17.5	18.0	18.7	19.4	53	88	121	86
May	21.4	24.0	21.2	24.0	79	83	114	146
June	26.0	27.2	24.9	27.4	135	70	145	64
July	26.8	27.7	28.4	28.4	156	142	44	270
August	27.3	26.9	27.5	27.0	66	143	244	186
September	23.5	23.7	23.8	24.9	61	74	87	267
October	19.9	17.5	18.7	19.5	46	41	80	0
November	11.6	15.0	13.4	16.3	3	78	48	186
December	14.1	9.6	11.0	10.4	99	62	119	77

Table 5.2: Initial soil properties of the 0-15 cm and 15-30 cm soil depths of the study site.

Soil depth	OM	pH	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu
cm	g kg^{-1}		mg kg^{-1}								
0-15	8.6	6.64	45.6	37.4	29.8	303	0.19	4.34	16.8	28.3	1.98
15-30	8.3	6.71	44.4	31.1	22.1	315	0.19	3.76	14.4	26.5	1.65

Abbreviations: OM, organic matter.

Table 5.3: Impacts of management systems on water infiltration in the corn-peanut-cotton, peanut-cotton-corn, and cotton-corn-peanut sequences in 2022, 2023, and 2024.

Management systems	Water infiltration (m day^{-1})		
	2022 After corn	2023 After peanut	2024 After cotton
CT	4.27±1.13a	6.67±1.15a	3.29±0.90a
RT	2.57±0.70a	5.01±1.16a	3.41±0.65a
RT+CR	3.94±0.73a	5.31±0.52a	2.34±0.30a
RT+CR+PL	3.44±0.68a	6.12±0.94a	2.42±0.68a
RT+CR+PL+BC	2.83±0.80a	5.53±0.27a	1.17±0.05a
	2022 After peanut	2023 After cotton	2024 After corn
CT	7.62±1.15a	4.53±0.16a	3.47±0.63a
RT	6.33±0.48a	4.07±0.34a	3.50±0.79a
RT+CR	4.32±0.55a	3.78±0.68a	3.42±0.64a
RT+CR+PL	5.78±1.18a	4.53±0.34a	4.22±0.64a
RT+CR+PL+BC	6.11±0.64a	4.07±0.18a	4.14±0.75a
	2022 After cotton	2023 After corn	2024 After peanut
CT	6.57±0.99a	4.86±0.78a	4.82±0.49a
RT	4.09±0.80a	3.80±0.47a	4.13±0.53a
RT+CR	5.67±0.59a	4.34±1.17a	3.90±0.43a
RT+CR+PL	7.06±1.22a	4.66±0.64a	4.55±1.03a
RT+CR+PL+BC	6.93±0.61a	4.75±0.27a	5.35±1.04a

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table 5.4: Impacts of management systems on bulk density in the corn-peanut-cotton, peanut-cotton-corn, and cotton-corn-peanut sequences in 2022, 2023, and 2024.

Management systems	Bulk density ($g\ cm^{-3}$)					
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
	2022 After corn		2023 After peanut		2024 After cotton	
CT	1.43±0.07a	1.34±0.10a	-	-	1.28±0.08a	1.78±0.12a
RT	1.50±0.05a	1.54±0.05a	-	-	1.37±0.06a	1.68±0.17a
RT+CR	1.53±0.08a	1.56±0.03a	-	-	1.42±0.06a	1.64±0.09a
RT+CR+PL	1.44±0.09a	1.51±0.04a	-	-	1.24±0.05a	1.62±0.15a
RT+CR+PL+BC	1.48±0.04a	1.39±0.12a	-	-	1.31±0.04a	1.66±0.17a
	2022 After peanut		2023 After cotton		2024 After corn	
CT	1.40±0.02a	1.50±0.06a	1.42±0.03a	1.41±0.06a	1.36±0.03a	1.50±0.07a
RT	1.46±0.02a	1.53±0.06a	1.38±0.01a	1.43±0.05a	1.45±0.03a	1.39±0.08a
RT+CR	1.39±0.03a	1.53±0.10a	1.40±0.03a	1.44±0.04a	1.39±0.07a	1.46±0.10a
RT+CR+PL	1.42±0.07a	1.60±0.13a	1.37±0.03a	1.45±0.04a	1.36±0.05a	1.47±0.12a
RT+CR+PL+BC	1.40±0.01a	1.50±0.06a	1.38±0.03a	1.49±0.13a	1.32±0.07a	1.58±0.18a
	2022 After cotton		2023 After corn		2024 After peanut	
CT	1.33±0.09a	1.32±0.10a	-	-	1.45±0.03a	1.51±0.04a
RT	1.45±0.11a	1.37±0.09a	-	-	1.45±0.04a	1.59±0.08a
RT+CR	1.49±0.09a	1.38±0.04a	-	-	1.51±0.03a	1.53±0.05a
RT+CR+PL	1.43±0.16a	1.53±0.07a	-	-	1.44±0.04a	1.64±0.03a
RT+CR+PL+BC	1.45±0.08a	1.39±0.11a	-	-	1.56±0.05a	1.46±0.04a

Within a column in each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table 5.5: Impacts of management systems on volumetric water content in the corn-peanut-cotton, peanut-cotton-corn, and cotton-corn-peanut sequences in 2022, 2023, and 2024.

Management systems	Volumetric water content ($cm^3 cm^{-3}$)					
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
	2022 After corn		2023 After peanut		2024 After cotton	
CT	0.13±0.01a	0.14±0.02a	-	-	0.15±0.01a	0.20±0.02a
RT	0.15±0.00a	0.18±0.01a	-	-	0.16±0.00a	0.20±0.03a
RT+CR	0.14±0.01a	0.17±0.02a	-	-	0.19±0.01a	0.20±0.01a
RT+CR+PL	0.12±0.01a	0.16±0.02a	-	-	0.16±0.01a	0.19±0.02a
RT+CR+PL+BC	0.12±0.01a	0.16±0.02a	-	-	0.18±0.00a	0.18±0.03a
	2022 After peanut		2023 After cotton		2024 After corn	
CT	0.12±0.00a	0.13±0.01a	0.08±0.00a	0.09±0.01a	0.08±0.01a	0.10±0.01a
RT	0.12±0.00a	0.13±0.00a	0.07±0.00a	0.08±0.01a	0.08±0.00a	0.10±0.01a
RT+CR	0.12±0.00a	0.13±0.01a	0.07±0.00a	0.09±0.00a	0.06±0.01a	0.09±0.01a
RT+CR+PL	0.12±0.01a	0.12±0.01a	0.07±0.00a	0.09±0.01a	0.06±0.01a	0.08±0.02a
RT+CR+PL+BC	0.13±0.01a	0.12±0.01a	0.07±0.00a	0.08±0.01a	0.06±0.01a	0.10±0.02a
	2022 After cotton		2023 After corn		2024 After peanut	
CT	0.09±0.01a	0.14±0.04a	-	-	0.07±0.00a	0.09±0.00a
RT	0.12±0.01a	0.13±0.01a	-	-	0.07±0.01a	0.10±0.01a
RT+CR	0.11±0.01a	0.08±0.01a	-	-	0.07±0.01a	0.09±0.00a
RT+CR+PL	0.11±0.02a	0.11±0.01a	-	-	0.08±0.01a	0.10±0.01a
RT+CR+PL+BC	0.12±0.01a	0.10±0.01a	-	-	0.08±0.01a	0.09±0.00a

Within a column in each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table 5.6: Impacts of management systems on soil respiration in the corn-peanut-cotton, peanut-cotton-corn, and cotton-corn-peanut sequences in 2022, 2023, and 2024.

Management systems	Soil respiration (g CO_2 kg^{-1} h^{-1})					
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
	2022 After corn		2023 After peanut		2024 After cotton	
CT	2.47±0.11a	0.86±0.19a	2.40±0.19a	0.92±0.12a	2.45±0.16a	0.91±0.12a
RT	2.06±0.17a	0.86±0.22a	2.58±0.26a	1.13±0.16a	2.03±0.46a	0.62±0.18a
RT+CR	2.45±0.08a	0.82±0.13a	2.52±0.43a	0.88±0.13a	2.56±0.26a	0.86±0.12a
RT+CR+PL	2.32±0.15a	0.81±0.16a	2.66±0.14a	1.06±0.11a	2.72±0.22a	0.75±0.12a
RT+CR+PL+BC	1.99±0.15a	0.91±0.20a	3.07±0.51a	1.19±0.10a	2.21±0.36a	0.72±0.14a
	2022 After peanut		2023 After cotton		2024 After corn	
CT	2.47±0.04a	0.52±0.15a	1.85±0.40a	0.67±0.12a	1.87±0.14a	0.69±0.12a
RT	2.47±0.17a	0.49±0.02a	1.67±0.21a	0.73±0.16a	1.86±0.08a	0.63±0.13a
RT+CR	2.42±0.36a	0.49±0.11a	2.15±0.19a	0.90±0.09a	2.08±0.14a	0.70±0.07a
RT+CR+PL	2.31±0.22a	0.55±0.07a	2.24±0.08a	0.90±0.13a	2.24±0.13a	0.76±0.11a
RT+CR+PL+BC	2.39±0.37a	0.59±0.12a	2.40±0.16a	0.77±0.13a	2.00±0.16a	0.80±0.18a
	2022 After cotton		2023 After corn		2024 After peanut	
CT	2.39±0.36a	0.87±0.17a	1.72±0.10a	0.76±0.17a	1.86±0.09a	0.77±0.07a
RT	2.51±0.35a	0.97±0.21a	1.79±0.03a	0.68±0.18a	1.89±0.11a	0.70±0.20a
RT+CR	2.88±0.13a	0.97±0.15a	2.17±0.10a	0.62±0.05a	1.87±0.15a	0.86±0.17a
RT+CR+PL	2.54±0.35a	0.95±0.13a	1.66±0.35a	0.68±0.07a	1.99±0.05a	1.02±0.17a
RT+CR+PL+BC	3.12±0.42a	0.77±0.20a	2.17±0.32a	0.57±0.06a	1.79±0.05a	0.56±0.07a

Within a column in each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table 5.7: Impacts of management systems on organic matter in the corn-peanut-cotton, peanut-cotton-corn, and cotton-corn-peanut sequences in 2022, 2023, and 2024.

Management systems	Organic matter (g kg^{-1})					
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
	2022 After corn		2023 After peanut		2024 After cotton	
CT	9.62±0.83a	9.43±1.10a	10.45±0.89a	10.54±1.42a	10.67±0.48a	7.69±0.52a
RT	9.18±0.50a	9.72±1.10a	10.16±0.51a	10.27±1.22a	11.14±0.37a	8.02±1.00a
RT+CR	10.02±0.32a	9.56±1.28a	10.68±0.43a	10.06±1.42a	12.85±1.16a	8.29±0.74a
RT+CR+PL	10.33±0.56a	10.77±1.10a	11.13±0.30a	10.49±0.78a	12.15±0.83a	7.81±0.63a
RT+CR+PL+BC	10.23±0.68a	12.42±2.05a	12.27±1.28a	10.07±1.23a	13.55±1.71a	7.26±0.28a
	2022 After peanut		2023 After cotton		2024 After corn	
CT	8.22±0.19a	5.96±0.56a	8.11±0.19a	6.36±0.64a	9.22±0.35a	6.64±0.44a
RT	7.96±0.29a	6.54±0.62a	7.68±0.25a	6.06±0.25a	8.36±0.12a	6.64±0.18a
RT+CR	7.95±0.33a	6.06±0.15a	8.38±0.60a	6.15±0.06a	9.05±0.31a	7.04±0.26a
RT+CR+PL	8.50±0.51a	5.70±0.13a	8.45±0.24a	6.68±0.41a	9.38±0.68a	7.08±0.50a
RT+CR+PL+BC	8.42±0.26a	6.05±0.29a	10.23±0.34a	6.44±0.43a	10.09±0.43a	7.80±0.78a
	2022 After cotton		2023 After corn		2024 After peanut	
CT	9.81±0.55a	9.15±0.99a	9.65±0.78a	8.60±0.99a	9.34±0.74a	7.81±0.49a
RT	10.69±1.27a	9.29±1.98a	9.92±1.65a	9.63±2.20a	10.09±1.60a	9.86±2.28a
RT+CR	9.85±0.95a	9.10±1.56a	10.09±0.95a	8.95±1.69a	9.68±1.63a	9.07±1.01a
RT+CR+PL	10.23±1.35a	9.50±1.35a	11.13±1.27a	9.87±1.44a	9.97±1.36a	9.43±1.22a
RT+CR+PL+BC	10.71±1.36a	8.11±0.42a	11.72±1.23a	9.81±1.48a	9.86±0.79a	8.53±0.83a

Within a column in each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table 5.8: Impacts of management systems on soil pH and nutrients in the corn-peanut-cotton sequence in 2022, 2023, and 2024.

Management systems	pH	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu
		mg kg^{-1}								
	2022 After corn (0-15 cm)									
CT	6.89±0.07a	53.4±3.5a	100±16a	68±11a	358±36a	0.24±0.06a	5.12±0.28a	12.8±0.4a	26.0±1.3a	0.26±0.03ab
RT	6.93±0.15a	48.4±3.2a	111±13a	39±6a	289±27a	0.19±0.01a	4.53±0.26a	11.9±0.3a	28.7±0.9a	0.19±0.01b
RT+CR	6.85±0.09a	46.9±5.2a	88±11a	44±4a	314±22a	0.23±0.02a	4.96±0.33a	13.0±0.6a	33.3±2.6a	0.26±0.02ab
RT+CR+PL	6.99±0.10a	50.0±4.6a	111±16a	50±7a	310±43a	0.26±0.04a	5.35±0.81a	12.9±1.5a	29.9±5.8a	0.44±0.06a
RT+CR+PL+BC	6.94±0.15a	50.6±6.1a	87±11a	53±5a	359±29a	0.26±0.03a	5.14±0.40a	13.4±0.8a	27.5±5.5a	0.36±0.04ab
	2022 After corn (15-30 cm)									
CT	6.65±0.07a	31.6±8.3a	96±15a	41±7a	349±43a	0.38±0.10a	2.88±0.87a	9.5±0.9a	20.6±2.5a	0.27±0.03a
RT	6.56±0.10a	27.0±7.2a	101±14a	40±4a	393±9a	0.39±0.10a	2.12±0.30a	10.9±1.2a	24.4±2.2a	0.37±0.03a
RT+CR	6.76±0.07a	25.5±7.2a	93±12a	40±9a	362±41a	0.39±0.11a	2.27±0.40a	9.6±1.1a	27.8±6.5a	0.29±0.02a
RT+CR+PL	6.66±0.15a	23.9±6.1a	142±28a	48±7a	394±36a	0.55±0.12a	2.55±0.55a	9.7±1.3a	19.5±2.1a	0.32±0.03a
RT+CR+PL+BC	6.43±0.12a	20.9±8.6a	160±43a	49±8a	442±7a	0.56±0.14a	1.87±0.54a	10.4±0.9a	14.8±2.4a	0.36±0.08a
	2023 After peanut (0-15 cm)									
CT	6.93±0.03a	52.8±3.2b	53±6a	83±9a	489±36a	0.33±0.07a	4.94±0.70b	11.1±0.9a	29.6±2.7a	0.24±0.04b
RT	6.91±0.03a	51.2±3.7b	57±7a	80±7a	462±16a	0.31±0.03a	5.30±0.38ab	12.8±0.8a	32.5±3.9a	0.24±0.07b
RT+CR	6.88±0.03a	45.4±4.9b	44±2a	92±19a	538±53a	0.32±0.03a	5.25±0.23ab	13.6±1.0a	27.0±3.3a	0.18±0.02b
RT+CR+PL	6.88±0.02a	87.5±6.1a	69±7a	103±13a	575±39a	0.36±0.03a	8.09±0.96a	13.6±0.5a	29.6±1.4a	0.69±0.05a
RT+CR+PL+BC	6.91±0.03a	69.1±5.6ab	54±2a	103±9a	593±45a	0.36±0.02a	6.24±0.22ab	14.4±0.9a	27.1±3.1a	0.50±0.05a
	2023 After peanut (15-30 cm)									
CT	6.64±0.12a	38.1±11.8a	111±30a	45±7a	300±58a	0.50±0.15a	2.18±0.21a	8.3±0.5a	24.9±3.2a	0.36±0.07ab
RT	6.71±0.11a	32.0±9.2a	90±20a	46±5a	280±40a	0.49±0.12a	3.61±0.89a	10.7±1.0a	27.2±0.9a	0.33±0.03ab
RT+CR	6.72±0.09a	27.7±6.8a	83±19a	58±9a	317±85a	0.44±0.11a	2.98±0.37a	10.5±1.3a	27.9±6.5a	0.28±0.02b
RT+CR+PL	6.73±0.04a	35.5±5.5a	118±11a	48±9a	328±55a	0.50±0.09a	3.78±0.47a	10.8±0.9a	32.8±2.8a	0.48±0.02ab
RT+CR+PL+BC	6.74±0.03a	36.7±5.8a	97±12a	45±10a	331±48a	0.43±0.06a	3.90±0.08a	11.1±0.8a	25.6±2.2a	0.55±0.09a

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Table 5.8 continued…

Management systems	pH	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu
		mg kg^{-1}								
	2024 After cotton (0-15 cm)									
CT	7.31±0.05a	55.9±3.0c	122±13a	98±6a	661±22a	0.38±0.04a	6.34±0.59b	13.3±0.4b	30.0±3.8a	0.32±0.01c
RT	6.96±0.08a	60.1±1.1bc	100±17a	121±11a	717±50a	0.41±0.06a	8.29±0.75ab	14.8±1.1ab	36.9±4.7a	0.37±0.02c
RT+CR	7.12±0.11a	55.1±3.0c	94±18a	136±25a	770±94a	0.55±0.10a	7.97±0.87ab	14.4±1.0ab	31.4±5.1a	0.36±0.02c
RT+CR+PL	7.12±0.15a	109.4±10.6a	122±15a	148±22a	912±123a	0.49±0.07a	11.86±1.79a	16.3±0.9ab	30.1±2.9a	1.33±0.21a
RT+CR+PL+BC	7.12±0.10a	83.7±6.0ab	101±11a	159±29a	952±170a	0.72±0.10a	11.71±1.86a	17.9±2.1a	32.7±6.9a	0.70±0.05b
	2024 After cotton (15-30 cm)									
CT	6.43±0.11a	28.6±5.2a	64±10a	42±4a	334±35a	0.26±0.02a	3.43±0.48a	7.4±0.8a	25.0±4.1a	0.28±0.04a
RT	6.38±0.17a	28.6±7.0a	99±8a	40±7a	295±43a	0.30±0.06a	2.83±0.60a	6.3±0.9a	20.0±1.9a	0.26±0.03a
RT+CR	6.44±0.04a	35.8±9.7a	113±9a	52±4a	358±16a	0.36±0.06a	4.23±0.76a	9.1±1.4a	28.3±1.6a	0.50±0.07a
RT+CR+PL	6.43±0.09a	30.5±3.4a	86±17a	40±7a	360±35a	0.33±0.06a	3.81±0.37a	8.4±0.8a	25.0±5.0a	0.38±0.06a
RT+CR+PL+BC	6.50±0.09a	39.8±6.7a	94±17a	46±4a	350±16a	0.28±0.03a	4.43±1.00a	9.1±0.8a	23.6±3.5a	0.46±0.10a

Within a column in each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table 5.9: Impacts of management systems on soil pH and nutrients in the peanut-cotton-corn sequence in 2022, 2023, and 2024.

Management systems	pH	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu
		mg kg^{-1}								
	2022 After peanut (0-15 cm)									
CT	6.88±0.12a	48.1±3.7a	40.9±4.5a	65.9±9.7a	415±22a	0.20±0.01a	4.14±0.24a	11.9±0.7a	24.5±0.8a	0.22b
RT	7.03±0.04a	39.8±2.7a	41.4±3.9a	49.5±5.3ab	374±47a	0.16±0.01a	3.68±0.35a	10.7±0.5a	25.5±1.4a	0.30ab
RT+CR	6.90±0.05a	41.1±3.2a	42.2±1.0a	42.7±5.3ab	329±13a	0.19±0.01a	3.56±0.19a	11.2±0.4a	30.6±3.3a	0.25b
RT+CR+PL	6.99±0.04a	40.4±3.3a	47.4±6.3a	37.2±3.6b	358±58a	0.20±0.04a	6.08±1.99a	13.1±1.6a	26.4±0.9a	0.85a
RT+CR+PL+BC	6.89±0.08a	60.5±8.8a	48.6±6.8a	65.8±5.8a	401±27a	0.24±0.01a	4.96±0.28a	13.5±1.2a	29.9±1.3a	0.56ab
	2022 After peanut (15-30 cm)									
CT	6.90±0.12a	40.6±4.8a	41.3±12.6a	24.6±5.4a	272±24a	0.16±0.06a	2.08±0.21a	7.5±0.6a	27.9±1.3a	0.51a
RT	6.93±0.03a	38.4±9.6a	31.6±4.1a	21.6±4.8a	253±15a	0.21±0.10a	1.88±0.22a	8.2±1.0a	27.7±2.7a	0.47a
RT+CR	6.93±0.05a	42.2±9.1a	41.1±6.1a	21.7±2.3a	283±19a	0.16±0.02a	2.22±0.13a	7.9±0.4a	29.1±4.2a	0.50a
RT+CR+PL	6.87±0.06a	35.1±8.2a	48.8±11.4a	15.6±2.6a	222±22a	0.13±0.02a	2.34±0.61a	8.2±1.0a	26.8±0.9a	0.52a
RT+CR+PL+BC	6.81±0.11a	41.5±3.5a	47.1±9.3a	22.2±3.8a	250±18a	0.14±0.02a	2.23±0.30a	7.9±0.3a	29.5±3.8a	0.46a
	2023 After cotton (0-15 cm)									
CT	7.33±0.04a	34.2±2.4a	51.6±4.8a	63.6±8.2a	355±23a	0.30±0.04a	2.41±0.32a	7.4±0.8a	10.8±0.8a	0.14a
RT	7.12±0.12a	31.2±3.7a	53.0±2.1a	55.7±9.4a	305±35a	0.26±0.02a	2.48±0.14a	6.8±0.4a	10.8±0.6a	0.15a
RT+CR	7.24±0.07a	32.1±3.9a	46.2±3.5a	54.0±6.6a	335±42a	0.30±0.03a	2.95±0.54a	7.2±0.4a	11.0±0.8a	0.15a
RT+CR+PL	7.15±0.08a	47.5±5.6a	60.2±7.4a	74.2±14.2a	344±29a	0.29±0.01a	3.22±0.21a	8.7±1.4a	11.1±1.0a	0.35a
RT+CR+PL+BC	7.38±0.09a	44.0±3.4a	53.6±5.9a	85.9±9.1a	444±34a	0.37±0.01a	3.24±0.21a	8.8±0.3a	11.1±1.1a	0.26a
	2023 After cotton (15-30 cm)									
CT	6.86±0.12a	34.8±3.6a	48.0±14.9a	28.8±3.1a	251±14a	0.18±0.05a	1.50±0.17a	5.0±0.4a	12.0±0.6a	0.25a
RT	6.83±0.15a	36.6±4.1a	39.3±6.1a	30.4±8.7a	265±32a	0.16±0.02a	1.59±0.13a	5.7±0.6a	13.4±0.7a	0.19a
RT+CR	6.86±0.04a	34.4±4.9a	43.4±5.8a	25.7±3.6a	260±21a	0.18±0.01a	1.61±0.02a	5.2±0.2a	12.9±1.1a	0.22a
RT+CR+PL	6.95±0.03a	33.4±2.6a	68.9±12.0a	26.1±1.1a	236±21a	0.23±0.02a	1.76±0.23a	5.3±0.5a	11.6±0.8a	0.24a
RT+CR+PL+BC	6.97±0.16a	32.6±1.9a	60.5±9.9a	36.1±7.6a	264±30a	0.17±0.04a	1.62±0.23a	5.6±0.6a	11.6±0.8a	0.21a

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Table 5.9 continued…

Management systems	pH	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu
		mg kg^{-1}								
	2024 After corn (0-15 cm)									
CT	7.13±0.16a	45.8±7.9a	61.5±7.9a	74.1±13.9a	469±58a	0.52±0.10a	3.62±0.18a	11.2±1.1a	31.8±4.8a	0.23c
RT	6.89±0.12a	52.1±8.7a	52.7±5.8a	59.5±6.2a	374±40a	0.43±0.05a	3.32±0.33a	9.3±0.4a	28.1±2.1a	0.17c
RT+CR	7.02±0.10a	39.1±6.9a	55.5±9.4a	60.6±6.8a	386±38a	0.43±0.07a	3.71±0.33a	10.6±2.7a	24.9±2.2a	0.25c
RT+CR+PL	7.19±0.10a	61.7±3.7a	58.0±7.0a	81.6±12.2a	496±64a	0.55±0.12a	5.80±1.17a	10.0±0.4a	26.9±1.8a	1.77a
RT+CR+PL+BC	7.22±0.05a	56.9±4.8a	52.7±9.1a	82.1±7.2a	509±20a	0.58±0.07a	4.53±0.07a	10.1±0.5a	27.5±3.5a	0.88b
	2024 After corn (15-30 cm)									
CT	6.92±0.12a	42.6±3.7a	54.2±6.8a	34.9±4.8a	292±33a	0.31±0.07a	2.41±0.52a	7.0±0.6a	35.7±3.0a	0.44a
RT	6.69±0.06a	43.8±5.5a	50.8±0.4a	28.7±3.0a	269±12a	0.25±0.05a	2.69±0.37a	7.1±0.2a	34.2±2.4a	0.41a
RT+CR	6.87±0.19a	40.5±7.7a	46.6±7.0a	28.8±2.2a	236±20a	0.27±0.08a	3.52±0.18a	8.9±0.1a	30.5±1.1a	0.39a
RT+CR+PL	6.80±0.11a	42.4±8.4a	59.3±18.8a	39.5±4.6a	258±39a	0.38±0.19a	3.54±0.81a	7.6±0.7a	28.8±1.6a	0.91a
RT+CR+PL+BC	6.94±0.10a	43.4±6.8a	87.7±20.4a	50.6±3.4a	301±32a	0.46±0.14a	2.89±0.33a	7.2±0.4a	29.8±2.8a	0.63a

Within a column in each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table 5.10: Impacts of management systems on soil pH and nutrients in the cotton-corn-peanut sequence in 2022, 2023, and 2024.

Management systems	pH	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu
		mg kg^{-1}								
	2022 After cotton (0-15 cm)									
CT	6.85±0.02a	50.9±6.3a	58.5±2.9a	54.5±1.9a	453±5a	0.25±0.01a	4.51±0.24a	17.3±1.3a	31.4±7.5a	0.62±0.18a
RT	6.61±0.13a	47.3±5.1a	55.2±3.9a	48.5±5.0a	427±4a	0.28±0.02a	5.14±0.15a	19.8±2.5a	30.6±2.3a	0.42±0.06a
RT+CR	6.83±0.12a	52.5±4.1a	67.5±11.7a	61.4±2.2a	465±25a	0.28±0.02a	4.58±0.47a	18.2±0.6a	37.6±4.6a	0.38±0.03a
RT+CR+PL	6.75±0.14a	62.7±7.8a	81.9±9.6a	55.4±8.2a	447±67a	0.26±0.04a	5.14±0.69a	19.4±1.3a	29.6±2.5a	0.61±0.09a
RT+CR+PL+BC	6.77±0.17a	67.2±5.5a	59.9±7.8a	64.1±16.8a	481±48a	0.28±0.03a	5.22±0.52a	18.3±1.1a	38.1±0.9a	0.51±0.04a
	2022 After cotton (15-30 cm)									
CT	7.07±0.05a	33.8±7.7a	72.3±5.8a	47.5±5.6a	485±34a	0.26±0.02a	1.69±0.18a	11.8±1.0a	19.8±6.2a	0.41±0.03a
RT	6.89±0.11a	32.6±9.0a	53.7±11.5a	46.0±10.6a	461±74a	0.22±0.03a	1.83±0.21a	12.3±1.1a	23.5±6.8a	0.45±0.07a
RT+CR	7.02±0.08a	47.4±7.6a	60.6±11.6a	40.5±6.3a	438±39a	0.22±0.02a	2.29±0.13a	14.3±1.4a	23.9±4.9a	0.49±0.08a
RT+CR+PL	6.92±0.03a	43.8±10.5a	87.0±19.8a	35.0±5.5a	430±46a	0.24±0.03a	2.45±0.45a	14.7±1.0a	25.2±7.7a	0.47±0.08a
RT+CR+PL+BC	6.94±0.04a	43.6±7.4a	78.4±13.9a	34.6±4.4a	383±2a	0.26±0.06a	2.02±0.26a	11.8±1.6a	20.0±2.4a	0.56±0.05a
	2023 After corn (0-15 cm)									
CT	6.97±0.09a	42.7±6.1a	62.6±3.5a	52.5±2.1a	416±18a	0.18±0.01a	3.77±0.29b	11.4±0.9a	35.6±4.5a	0.13±0.02bc
RT	6.82±0.05a	40.3±5.3a	63.1±9.4a	48.4±2.0a	380±34a	0.18±0.02a	4.36±0.13ab	13.0±1.5a	31.2±4.4a	0.15±0.05bc
RT+CR	6.90±0.07a	48.7±7.6a	49.9±6.6a	65.1±4.3a	470±23a	0.20±0.01a	4.56±0.41ab	12.4±0.5a	38.3±3.4a	0.07±0.03c
RT+CR+PL	7.02±0.06a	73.4±7.5a	83.5±13.2a	73.7±9.3a	521±73a	0.24±0.03a	6.62±0.75a	13.3±1.4a	36.4±3.8a	0.47±0.11a
RT+CR+PL+BC	6.82±0.06a	61.5±2.9a	60.6±8.6a	71.1±12.6a	494±61a	0.28±0.04a	5.73±0.35ab	13.8±0.9a	40.6±3.3a	0.30±0.04ab
	2023 After corn (15-30 cm)									
CT	6.97±0.10a	32.2±11.3a	54.6±8.2a	37.6±2.7a	388±14a	0.19±0.02a	1.78±0.34a	7.4±0.8a	32.2±5.0a	0.31±0.11a
RT	6.76±0.04a	26.1±10.3a	63.9±13.2a	33.5±3.8a	351±72a	0.17±0.04a	1.95±0.43a	8.5±1.1a	30.1±6.4a	0.21±0.04a
RT+CR	6.97±0.06a	34.7±12.5a	56.3±4.9a	39.5±4.6a	411±39a	0.19±0.02a	2.23±0.45a	9.0±0.8a	35.3±6.7a	0.28±0.10a
RT+CR+PL	6.78±0.04a	30.6±5.7a	86.7±22.1a	47.4±10.4a	444±63a	0.26±0.08a	1.93±0.22a	8.4±0.9a	31.2±3.6a	0.26±0.03a
RT+CR+PL+BC	6.78±0.06a	29.9±9.2a	75.8±14.1a	40.5±8.5a	413±31a	0.29±0.10a	1.81±0.35a	7.5±0.7a	38.8±2.4a	0.36±0.04a

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Table 5.10 continued…

Management systems	pH	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu
		mg kg^{-1}								
2024 After peanut (0-15 cm)										
CT	7.19±0.04a	50.6±5.8a	60.6±6.6a	80.4±8.3a	630±59a	0.54±0.02a	5.28±0.50b	14.9±1.2a	30.1±4.9a	0.41±0.05b
RT	6.87±0.01b	45.1±4.6a	55.4±7.2a	72.9±7.5a	535±75a	0.52±0.06a	5.66±0.40b	14.4±1.9a	31.9±3.7a	0.39±0.04b
RT+CR	6.87±0.05b	46.7±5.1a	46.6±8.7a	67.8±8.9a	570±70a	0.50±0.06a	5.18±0.51b	13.6±1.8a	33.0±2.9a	0.40±0.06b
RT+CR+PL	6.93±0.06ab	94.0±3.3a	74.4±11.1a	99.5±10.1a	658±71a	0.64±0.06a	10.22±2.19a	19.3±3.7a	36.5±3.1a	1.18±0.08a
RT+CR+PL+BC	6.98±0.04ab	77.6±6.3a	48.7±5.0a	99.2±3.2a	661±31a	0.58±0.02a	7.51±0.71ab	15.0±0.7a	31.8±1.8a	0.92±0.04a
2024 After peanut (15-30 cm)										
CT	6.88±0.04a	40.8±10.9a	46.4±6.5a	54.4±4.4a	540±54a	0.42±0.03a	3.19±0.67a	9.8±0.9a	36.7±7.6a	0.45±0.07a
RT	6.68±0.09a	37.8±11.4a	52.2±17.5a	50.0±3.9a	571±97a	0.48±0.11a	4.00±0.82a	10.6±0.7a	34.8±6.9a	0.48±0.04a
RT+CR	6.84±0.11a	45.5±9.9a	48.1±14.0a	59.4±9.1a	613±68a	0.49±0.05a	4.33±0.40a	13.1±1.8a	34.0±5.7a	0.46±0.05a
RT+CR+PL	6.75±0.01a	56.7±10.1a	108.4±9.3a	69.5±3.5a	609±41a	0.60±0.03a	4.72±0.35a	10.2±0.5a	34.3±3.1a	0.80±0.12a
RT+CR+PL+BC	6.76±0.05a	52.5±11.8a	71.1±18.9a	63.1±8.9a	561±24a	0.56±0.14a	4.24±0.56a	8.7±0.3a	34.1±4.7a	0.72±0.07a

Within a column in each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Figures

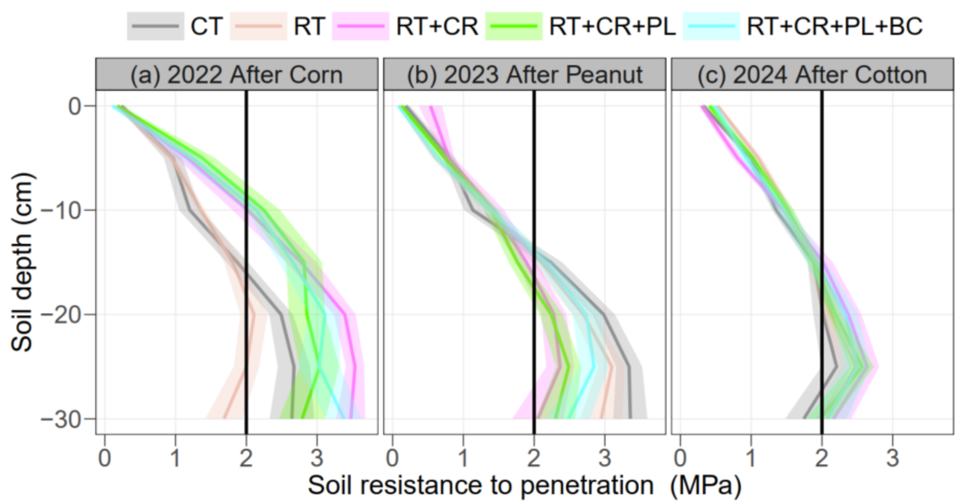

Figure 5.1. Impacts of management systems on soil resistance to penetration in the corn-peanut-cotton sequences in 2022, 2023, and 2024. The standard deviation of the mean (n = 20) in the line graphs is marked by colored ribbons. Penetration resistance values greater than 2 MPa indicate the soil is compacted or root growth will be restricted, as indicated by the black solid vertical lines. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

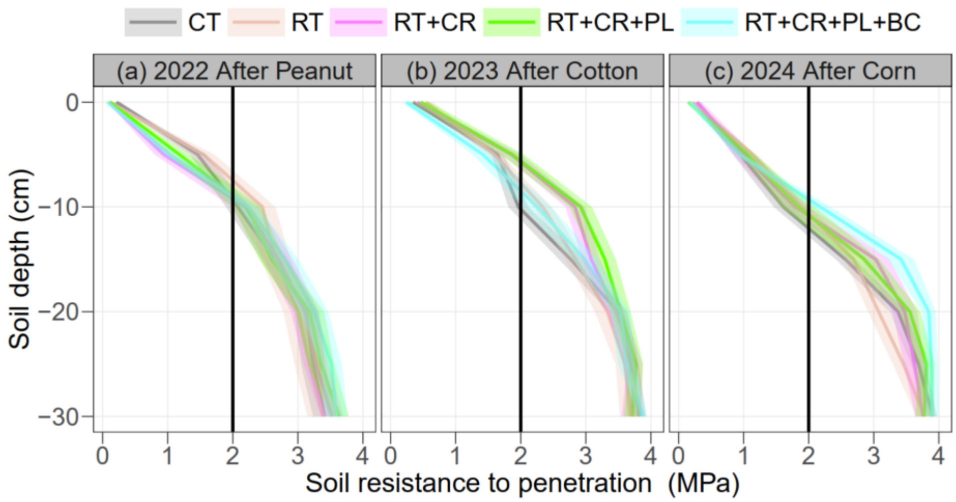

Figure 5.2. Impacts of management systems on soil resistance to penetration in the peanut-cotton-corn sequence in 2022, 2023, and 2024. The standard deviation of the mean (n = 20) in the line graphs is marked by colored ribbons. Penetration resistance values greater than 2 MPa indicate the soil is compacted or root growth will be restricted, as indicated by the black solid vertical lines. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

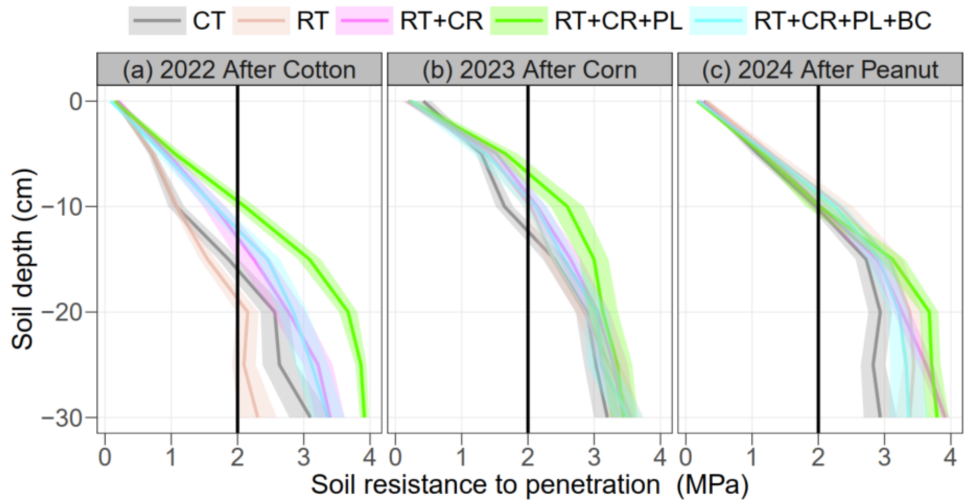

Figure 5.3. Impacts of management systems on soil resistance to penetration in the cotton-corn-peanut sequence in 2022, 2023, and 2024. The standard deviation of the mean (n = 20) in the line graphs is marked by colored ribbons. Penetration resistance values greater than 2 MPa indicate the soil is compacted or root growth will be restricted, as indicated by the black solid vertical lines. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Supplemental Tables

Table S5.1: Nutrient composition (dry basis) of organic amendments used in the study.

Organic amendment	Total C	Total N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
	---------- g kg $^{-1}$ ----------											
	---------- 2021 ----------											
Poultry litter	NA	15.5	7.3	22.9	3.96	13.5	3.44	0.07	0.22	0.3	0.3	0.45
Biochar	866	2.95	1.77	4.88	3.45	24	0.37	0.25	0.25	0.49	0.86	0.25
	---------- 2022 ----------											
Poultry litter	275	39.1	16.8	39.9	9.2	34.8	15.8	0.12	0.55	0.37	4.46	0.49
Biochar	866	2.95	1.77	4.88	3.45	24	0.37	0.25	0.25	0.49	0.86	0.25
	---------- 2023 ----------											
Poultry litter	311	43.1	41.8	48.3	9.06	33.8	14.2	0.14	0.41	0.32	2.43	0.41
Biochar	712	2.32	5.4	5.56	3.93	30.5	0.35	0.17	0.17	0.35	3.07	0.17

Table S5.2: Field operation dates for the duration of the study.

Field operations	Corn 2021/2022	Peanut 2022/2023	Cotton 2023/2024	Peanut 2021/2022	Cotton 2022/2023	Corn 2023/2024	Cotton 2021/2022	Corn 2022/2023	Peanut 2023/2024
Amendment application	Mar. 19, 2021	May 11, 2022	May 9, 2023	Apr. 1, 2021	May 11, 2022	Mar. 9, 2023	Apr. 1, 2021	Mar. 15, 2022	May 9, 2023
Tillage	April 7, 2021	May 12, 2022	May 12, 2023	Apr. 29, 2021	May 12, 2022	April 6, 2023	April 29, 2021	Mar. 25, 2022	May 12, 2023
Soil health assessment and sampling	Apr. 21, 2022	Apr. 20, 2023	Mar. 19, 2024	Apr. 22, 2022	Mar. 8, 2023	Apr. 25, 2024	Mar. 8, 2022	Apr. 20, 2023	Apr. 25, 2024

Table S5.3: Inorganic fertilizer rates and sources applied in the corn study in 2021, 2022, and 2023.

Nutrients	Rates (kg ha^{-1})			Nutrient sources
	CT, RT, and RT+CR	RT+CR+PL	RT+CR+PL+BC	
2021				
N	304	304	304	Diammonium phosphate; Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
P_2O_5	108	108	108	Diammonium phosphate
K_2O	202	202	202	Potassium chloride
S	13	13	13	Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
2022				
N	356	356	356	Diammonium phosphate; Ammonium polyphosphate; Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
P_2O_5	75	75	75	Diammonium phosphate; Ammonium polyphosphate
K_2O	185	185	185	Potassium chloride
S	21	21	21	Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)

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Table S5.3 continued…

Nutrients	Rates (kg ha^{-1})			Nutrient sources
	CT, RT, and RT+CR	RT+CR+PL	RT+CR+PL+BC	
2023				
N	280	168	224	Urea, Urea ammonium nitrate solution, Diammonium phosphate, Ammonium sulfate
P_2O_5	115	-	58	Diammonium phosphate
K_2O	168	-	84	Potassium chloride
S	11	-	-	Ammonium sulfate

Notes: In 2021 and 2022, all plots received the same amount of inorganic fertilizer. The full rates of P, K, and S were applied at pre-planting in 2021 and 2022 and at the V3 stage (three-leaf collar) in 2023. In 2021, 14%, 47%, and 39% of N was applied at the pre-plant, V3, and V6 stages, respectively. 16%, 42%, and 42% of the N was applied at the pre-plant, V4, and V6 stages, respectively, in 2022. In 2023, the initial (V3) percentage of N applied was 60% for CT, RT, and RT+CR, 33% for RT+CR+PL, and 50% for RT+CR+PL+BC. The remaining amount of N was applied at the V6 stage: 40% for CT, RT, and RT+CR; 67% for RT+CR+PL; 50% for RT+CR+PL+BC.

CT, Conventional tillage; RT, Reduced tillage; RT+CR, Reduced tillage with cereal rye; RT+CR+PL, Reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, Reduced tillage with cereal rye, poultry litter, and biochar.

Table S5.4: Inorganic fertilizer rates and sources applied in the cotton study in 2021, 2022, and 2023.

Nutrients	Rates (kg ha^{-1})			Nutrient sources
	CT, RT, and RT+CR	RT+CR+PL	RT+CR+PL+BC	
2021				
N	101	101	101	Super Rainbow Homogenized (28-0-0-5S); Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
P_2O_5	79	79	79	Triple super phosphate
K_2O	110	110	110	Potassium chloride
S	5	5	5	Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
B	0.6	0.6	0.6	Borosol
2022				
N	133	133	133	Diammonium phosphate; Ammonium sulfate; Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
P_2O_5	52	52	52	Diammonium phosphate
K_2O	101	101	101	Potassium chloride
S	10	10	10	Ammonium sulfate; Urea ammonium nitrate and ammonium thiosulfate solution (28-0-0-5S)
B	0.6	0.6	0.6	Borosol

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Table S5.4 continued…

Nutrients	Rates (kg ha^{-1})			Nutrient sources
	CT, RT, and RT+CR	RT+CR+PL	RT+CR+PL+BC	
2023				
N	84	-	28	Urea, Diammonium phosphate
P_2O_5	45	-	-	Diammonium phosphate
K_2O	78	-	-	Potassium chloride, Potassium sulfate
S	11	-	-	Potassium sulfate
B	0.6	-	-	Fertilizer Borate

Notes: In 2021 and 2022, all plots received the same amount of inorganic fertilizer. The full rates of P, K, S, and B were applied at pre-plant or early vegetative stage in all years. In 2023, the RT+CR+PL received no inorganic fertilizer. 12% and 88% of N was applied at the early vegetative stage and square stage, respectively, in 2021. In 2022, 33% of N was applied at pre-plant and 67% at the square stage. In 2023, the percentage of N applied at the early vegetative stage was 67% for CT, RT, and RT+CR. The remaining amount of N (33%) for the CT, RT, and RT+CR was applied at the square stage. All the N for the RT+CR+PL+BC was applied at the square stage. CT, Conventional tillage; RT, Reduced tillage; RT+CR, Reduced tillage with cereal rye; RT+CR+PL, Reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, Reduced tillage with cereal rye, poultry litter, and biochar.

Table S5.5: The *p*-values of the effects of the management systems on soil properties in the corn-peanut-cotton, peanut-cotton-corn, cotton-corn-peanut sequences.

Effect	SRP	Infiltration	Bulk density	VWC	Respiration	Organic matter	Soil pH	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu
	---------- Corn-peanut-cotton ----------															
Management (M)	0.077	0.222	0.761	0.470	0.753	0.653	0.832	**0.020**	0.580	0.612	0.253	0.679	**0.006**	**0.033**	0.730	**<0.001**
Depth (D)	**<0.001**	NA	**<0.001**	**0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.004**	**<0.001**	**<0.001**	0.063	**<0.001**	**<0.001**	**<0.001**	**0.006**
Year (Y)	**<0.001**	**<0.001**	0.477	**<0.001**	**0.004**	0.174	0.642	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.018**	**<0.001**	0.756	0.052	**<0.001**
M x D	0.509	NA	0.897	0.942	0.750	0.620	0.656	**<0.001**	0.213	0.313	0.827	0.611	0.205	0.801	0.442	**<0.001**
M x Y	**<0.001**	0.722	0.577	0.210	0.188	0.878	0.684	**0.041**	0.552	0.235	0.856	0.647	0.054	0.464	0.531	**0.006**
D x Y	**<0.001**	NA	**<0.001**	0.511	0.524	**<0.001**	**<0.001**	**0.020**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.003**	**<0.001**	**0.049**	**<0.001**
M x D x Y	**0.018**	NA	0.497	0.574	0.967	0.398	0.503	0.159	0.069	0.208	0.576	0.676	0.397	0.659	0.542	**0.002**
	---------- Peanut-cotton-corn ----------															
Management (M)	0.594	0.323	0.999	0.366	0.218	0.080	0.485	0.637	0.328	**0.032**	0.277	0.679	0.173	0.548	0.921	**<0.001**
Depth (D)	**<0.001**	NA	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.595	**<0.001**	**<0.001**	0.063	**<0.001**	**<0.001**	**<0.001**	0.142
Year (Y)	**0.003**	**<0.001**	0.160	**<0.001**	0.690	**<0.001**	**0.002**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
M x D	0.061	NA	0.530	0.632	0.998	0.075	0.937	**0.008**	0.144	0.505	**0.031**	0.611	**0.021**	0.113	0.559	**<0.001**
M x Y	0.750	0.342	0.988	**0.019**	0.754	0.198	0.185	0.171	0.819	0.069	0.320	0.665	0.615	0.703	**0.031**	**<0.001**
D x Y	**<0.001**	NA	0.591	**0.002**	**0.002**	0.968	**0.003**	0.452	0.674	0.592	**0.036**	**0.002**	**0.003**	0.135	0.160	0.423
M x D x Y	0.349	NA	0.846	0.752	0.810	0.354	0.806	0.792	0.665	0.495	0.772	0.330	0.845	0.942	0.962	0.564

Table S5.5 continued…

Effect	SRP	Infiltration	Bulk density	VWC	Respiration	Organic matter	Soil pH	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu
	---------- Cotton-corn-peanut ----------															
Management (M)	**<0.001**	0.104	0.415	0.320	0.803	0.980	**0.004**	0.129	0.113	0.357	0.871	0.510	**0.026**	0.481	0.940	**0.001**
Depth (D)	**<0.001**	NA	0.601	0.007	**<0.001**	**<0.001**	0.652	**<0.001**	0.050	**<0.001**	**0.005**	**0.040**	**<0.001**	**<0.001**	**<0.001**	0.635
Year (Y)	**0.011**	**0.005**	**0.005**	**<0.001**	**<0.001**	0.089	0.919	**<0.001**	0.194	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
M x D	**0.004**	NA	0.282	0.303	0.084	0.314	0.511	**<0.001**	0.066	0.174	0.063	0.973	**0.006**	0.058	0.827	**<0.001**
M x Y	**0.008**	0.870	0.931	0.377	0.658	0.369	0.825	0.062	0.453	0.045	0.170	0.264	0.200	0.893	0.342	**0.002**
D x Y	0.507	NA	0.185	**<0.001**	**0.033**	0.742	**<0.001**	0.301	0.816	0.505	0.393	0.229	**0.015**	0.623	**<0.001**	**0.032**
M x D x Y	0.113	NA	0.842	0.460	0.935	0.916	0.751	0.649	0.383	0.751	0.564	0.544	0.264	0.329	0.522	0.245

Table S5.6: Impacts of the management systems on soil resistance to penetration (SRP) in the corn-peanut-cotton sequence in 2022, 2023, and 2024.

Management systems	Soil resistance to penetration (MPa)					
	5cm	10cm	15cm	20cm	25cm	30cm
	2022 After corn					
CT	0.96±0.13a	1.20±0.15a	1.87±0.15a	2.49±0.17a	2.67±0.23a	2.64±0.31a
RT	0.95±0.06a	1.36±0.05a	1.81±0.12a	2.11±0.19a	2.00±0.18a	1.68±0.25a
RT+CR	1.16±0.15a	2.02±0.21a	2.77±0.21a	3.39±0.15a	3.54±0.13a	3.47±0.20a
RT+CR+PL	1.38±0.17a	2.25±0.23a	2.82±0.25a	2.86±0.26a	3.04±0.28a	2.79±0.32a
RT+CR+PL+BC	1.23±0.18a	2.14±0.15a	2.66±0.19a	3.11±0.22a	3.03±0.29a	3.38±0.24a
	2023 After peanut					
CT	0.80±0.08a	1.13±0.13a	2.24±0.16a	2.98±0.16a	3.34±0.18a	3.36±0.23a
RT	0.62±0.06a	1.38±0.12a	2.10±0.13a	2.70±0.15a	3.10±0.19a	2.94±0.26a
RT+CR	0.80±0.07a	1.42±0.14a	1.89±0.13a	2.27±0.17a	2.37±0.20a	2.02±0.24a
RT+CR+PL	0.74±0.08a	1.39±0.10a	1.76±0.12a	2.24±0.16a	2.49±0.16a	2.29±0.21a
RT+CR+PL+BC	0.63±0.05a	1.39±0.10a	2.16±0.12a	2.74±0.20a	2.85±0.20a	2.49±0.26a
	2024 After cotton					
CT	1.00±0.06a	1.36±0.06a	1.88±0.09a	2.02±0.14a	2.21±0.21a	1.74±0.24a
RT	1.10±0.05a	1.53±0.06a	1.88±0.09a	2.14±0.14a	2.47±0.20a	2.06±0.27a
RT+CR	0.81±0.07a	1.46±0.05a	2.01±0.14a	2.37±0.19a	2.66±0.15a	2.17±0.22a
RT+CR+PL	1.02±0.05a	1.52±0.08a	1.89±0.08a	2.19±0.10a	2.57±0.17a	1.98±0.19a
RT+CR+PL+BC	0.93±0.08a	1.47±0.11a	1.92±0.14a	2.33±0.17a	2.50±0.19a	2.07±0.29a

Within a column in each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table S5.7: Impacts of the management systems on soil resistance to penetration (SRP) in the peanut-cotton-corn sequence in 2022, 2023, and 2024.

Management systems	Soil resistance to penetration (MPa)					
	5cm	10cm	15cm	20cm	25cm	30cm
	---- 2022 After peanut ----					
CT	1.46±0.12a	2.08±0.19a	2.65±0.21a	3.13±0.19a	3.23±0.19a	3.41±0.18a
RT	1.55±0.16a	2.46±0.20a	2.66±0.23a	3.01±0.23a	3.18±0.23a	3.39±0.24a
RT+CR	0.94±0.14a	2.20±0.21a	2.70±0.23a	3.11±0.22a	3.28±0.19a	3.53±0.18a
RT+CR+PL	1.18±0.16a	2.22±0.22a	2.60±0.19a	3.18±0.22a	3.36±0.20a	3.64±0.15a
RT+CR+PL+BC	1.03±0.13a	2.24±0.14a	2.80±0.21a	3.25±0.22a	3.52±0.16a	3.59±0.17a
	---- 2023 After cotton ----					
CT	1.64±0.09a	1.96±0.16a	2.77±0.18a	3.49±0.14a	3.69±0.12a	3.82±0.11a
RT	1.59±0.11a	2.34±0.14a	2.84±0.15a	3.33±0.19a	3.60±0.14a	3.68±0.15a
RT+CR	1.86±0.14a	2.83±0.14a	3.08±0.14a	3.46±0.14a	3.75±0.12a	3.70±0.15a
RT+CR+PL	1.87±0.18a	2.92±0.17a	3.29±0.17a	3.54±0.15a	3.77±0.11a	3.71±0.12a
RT+CR+PL+BC	1.42±0.16a	2.25±0.22a	2.98±0.19a	3.53±0.14a	3.63±0.13a	3.88±0.06a
	---- 2024 After corn ----					
CT	0.95±0.11a	1.61±0.15a	2.56±0.15a	3.37±0.13a	3.69±0.11a	3.91±0.06a
RT	1.14±0.07a	1.89±0.11a	2.69±0.14a	3.07±0.16a	3.46±0.16a	3.78±0.12a
RT+CR	1.01±0.14a	1.79±0.21a	3.03±0.21a	3.48±0.19a	3.62±0.16a	3.76±0.12a
RT+CR+PL	1.04±0.11a	1.84±0.26a	2.85±0.23a	3.55±0.16a	3.81±0.12a	3.78±0.14a
RT+CR+PL+BC	0.94±0.06a	2.18±0.16a	3.42±0.20a	3.85±0.11a	3.89±0.10a	3.90±0.10a

Within a column in each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table S5.8: Impacts of the management systems on soil resistance to penetration (SRP) in the cotton-corn-peanut sequence in 2022, 2023, and 2024.

Management systems	Soil resistance to penetration (MPa)					
	5cm	10cm	15cm	20cm	25cm	30cm
	2022 After cotton					
CT	0.71±0.06a	1.08±0.12b	1.86±0.16bc	2.56±0.21b	2.63±0.26bc	3.10±0.32bc
RT	0.72±0.05a	1.08±0.07b	1.55±0.12c	2.15±0.16b	2.10±0.18c	2.30±0.29c
RT+CR	0.94±0.10a	1.65±0.17ab	2.25±0.25bc	2.77±0.26b	3.21±0.22ab	3.40±0.22ab
RT+CR+PL	1.06±0.12a	2.11±0.16a	3.09±0.17a	3.67±0.14a	3.86±0.09a	3.91±0.07a
RT+CR+PL+BC	0.88±0.11a	1.66±0.16ab	2.45±0.19ab	2.84±0.22b	3.12±0.25ab	3.36±0.25ab
	2023 After corn					
CT	1.30±0.08a	1.65±0.13b	2.40±0.18a	2.89±0.17a	3.03±0.18a	3.20±0.20a
RT	1.43±0.11a	2.04±0.12ab	2.38±0.14a	2.85±0.14a	3.23±0.17a	3.56±0.18a
RT+CR	1.52±0.13a	2.14±0.14ab	2.64±0.16a	3.05±0.19a	3.29±0.22a	3.44±0.18a
RT+CR+PL	1.66±0.18a	2.59±0.25a	3.00±0.22a	3.13±0.23a	3.35±0.23a	3.45±0.21a
RT+CR+PL+BC	1.37±0.19a	2.12±0.17ab	2.55±0.18a	3.04±0.18a	3.11±0.21a	3.52±0.22a
	2024 After peanut					
CT	1.08±0.09a	1.96±0.09a	2.72±0.16a	2.93±0.18a	2.83±0.19b	2.93±0.25b
RT	1.29±0.13a	2.33±0.19a	3.07±0.20a	3.38±0.17a	3.44±0.16ab	3.38±0.22ab
RT+CR	1.23±0.07a	2.04±0.13a	2.90±0.14a	3.26±0.13a	3.62±0.12ab	3.91±0.06a
RT+CR+PL	1.17±0.09a	2.02±0.21a	3.12±0.19a	3.68±0.14a	3.71±0.14a	3.79±0.18a
RT+CR+PL+BC	1.25±0.07a	2.26±0.16a	2.92±0.19a	3.22±0.16a	3.33±0.24ab	3.37±0.29ab

Within a column in each year and depth, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table S5.9: The *p*-values of the effects of the management systems on organic matter and nutrient stratification ratios in the corn-peanut-cotton, peanut-cotton-corn, cotton-corn-peanut sequences.

Effect	Organic matter ratio	P ratio	K ratio	Mg ratio	Ca ratio	Zn ratio	Mn ratio	Fe ratio	Cu ratio
	---------- Corn-peanut-cotton sequence ----------								
Management (M)	0.459	0.284	0.203	0.432	0.987	0.657	0.994	0.620	**<0.001**
Year (Y)	**<0.001**	0.455	**0.002**	**<0.001**	**<0.001**	0.081	**<0.001**	**0.015**	**<0.001**
M x Y	0.478	0.882	0.364	0.283	0.714	0.435	0.500	0.227	**<0.001**
	---------- Peanut-cotton-corn sequence ----------								
Management (M)	0.615	**0.023**	0.065	0.741	**0.015**	0.185	0.252	0.577	**<0.001**
Year (Y)	0.672	0.189	0.467	0.087	**0.034**	0.008	0.279	0.113	0.691
M x Y	0.260	0.925	0.624	0.420	0.822	0.728	0.885	0.898	0.780
	---------- Cotton-corn-peanut sequence ----------								
Management (M)	0.769	0.708	0.629	0.421	0.302	0.244	0.118	0.982	**0.007**
Year (Y)	0.528	**0.001**	0.621	0.638	0.217	**<0.001**	0.317	**<0.001**	**0.033**
M x Y	0.687	0.646	0.090	0.915	0.314	0.392	0.388	0.662	0.067

Note: *p*-values in bold text indicate significant effect terms ($P < 0.05$).

Table S5.10: Impacts of management systems on stratification ratios of organic matter and nutrients in the corn-peanut-cotton sequence in 2022, 2023, and 2024.

Management systems	Organic matter ratio	P ratio	K ratio	Mg ratio	Ca ratio	B ratio	Zn ratio	Mn ratio	Fe ratio	Cu ratio
	---------- 2022 After corn ----------									
CT	1.06±0.14a	2.24±0.73a	1.09±0.16a	1.72±0.17a	1.05±0.10a	0.74±0.18a	2.34±0.73a	1.39±0.12a	1.33±0.18a	1.00±0.21a
RT	0.98±0.11a	2.11±0.44a	1.13±0.11a	1.02±0.19a	0.72±0.06a	0.60±0.16a	2.29±0.39a	1.12±0.11a	1.20±0.08a	0.56±0.03a
RT+CR	1.09±0.11a	2.37±0.67a	1.00±0.19a	1.21±0.19a	0.90±0.12a	0.74±0.19a	2.39±0.39a	1.41±0.21a	1.33±0.21a	0.89±0.11a
RT+CR+PL	0.98±0.07a	2.66±0.75a	0.93±0.25a	1.06±0.05a	0.79±0.09a	0.53±0.11a	2.38±0.49a	1.41±0.24a	1.58±0.31a	1.43±0.26a
RT+CR+PL+BC	0.89±0.14a	3.37±0.82a	0.64±0.13a	1.15±0.14a	0.85±0.05a	0.59±0.17a	3.48±0.95a	1.31±0.12a	2.01±0.50a	1.07±0.14a
	---------- 2023 After peanut ----------									
CT	1.02±0.07a	1.95±0.67a	0.72±0.21a	1.98±0.29a	1.86±0.41a	0.85±0.25a	2.36±0.50a	1.36±0.17a	1.23±0.13a	0.74±0.19a
RT	1.02±0.09a	2.02±0.51a	0.80±0.26a	1.76±0.07a	1.78±0.31a	0.80±0.24a	1.74±0.37a	1.23±0.12a	1.21±0.18a	0.73±0.15a
RT+CR	1.11±0.12a	1.89±0.38a	0.65±0.19a	1.70±0.08a	2.12±0.58a	0.88±0.20a	1.86±0.27a	1.36±0.18a	1.04±0.12a	0.67±0.09a
RT+CR+PL	1.07±0.05a	2.79±0.74a	0.55±0.02a	2.33±0.44a	1.86±0.24a	0.76±0.05a	2.30±0.52a	1.29±0.13a	0.91±0.05a	1.46±0.16a
RT+CR+PL+BC	1.23±0.04a	1.97±0.21a	0.60±0.11a	2.52±0.34a	1.84±0.11a	0.91±0.13a	1.60±0.06a	1.30±0.06a	1.05±0.05a	0.96±0.11a
	---------- 2024 After cotton ----------									
CT	1.40±0.05a	2.12±0.34a	2.03±0.32a	2.40±0.25a	2.06±0.26a	1.56±0.28a	1.89±0.16a	1.87±0.22a	1.29±0.24a	1.22±0.17bc
RT	1.45±0.16a	2.53±0.61a	1.11±0.20a	3.57±1.14a	2.70±0.67a	1.48±0.38a	3.30±0.67a	2.41±0.23a	1.86±0.18a	1.51±0.27bc
RT+CR	1.60±0.22a	2.06±0.67a	0.88±0.23a	2.57±0.31a	2.15±0.23a	1.70±0.45a	2.21±0.63a	1.72±0.28a	1.13±0.22a	0.73±0.08c
RT+CR+PL	1.57±0.08a	3.73±0.53a	1.66±0.51a	3.80±0.54a	2.56±0.30a	1.53±0.14a	3.24±0.64a	1.98±0.15a	1.43±0.38a	3.59±0.51a
RT+CR+PL+BC	1.89±0.29a	2.28±0.38a	1.27±0.39a	3.62±0.90a	2.74±0.52a	2.70±0.69a	2.97±0.60a	2.06±0.38a	1.50±0.36a	1.66±0.23b

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table S5.11: Impacts of management systems on stratification ratios of organic matter and nutrients in the peanut-cotton-corn sequence in 2022, 2023, and 2024.

Management systems	Organic matter ratio	P ratio	K ratio	Mg ratio	Ca ratio	B ratio	Zn ratio	Mn ratio	Fe ratio	Cu ratio
	2022 After peanut									
CT	1.42±0.14a	1.28±0.28a	1.22±0.28a	2.85±0.46a	1.55±0.08a	1.54±0.29a	2.07±0.33a	1.61±0.15a	0.92±0.05a	0.47±0.10a
RT	1.25±0.12a	1.18±0.19a	1.53±0.16a	2.46±0.31a	1.30±0.07a	1.15±0.29a	2.09±0.42a	1.35±0.16a	0.93±0.07a	0.72±0.16a
RT+CR	1.31±0.06a	1.08±0.17a	1.10±0.16a	2.06±0.37a	1.18±0.09a	1.25±0.13a	1.62±0.13a	1.44±0.11a	1.09±0.12a	0.54±0.11a
RT+CR+PL	1.50±0.11a	1.59±0.40a	1.05±0.12a	2.20±0.23a	1.64±0.27a	1.53±0.30a	3.02±0.85a	1.65±0.22a	0.98±0.04a	1.63±1.00a
RT+CR+PL+BC	1.40±0.04a	1.44±0.11a	1.06±0.06a	3.21±0.59a	1.61±0.06a	1.81±0.17a	2.32±0.31a	1.72±0.16a	1.06±0.13a	1.52±0.65a
	2023 After cotton									
CT	1.31±0.14a	1.00±0.09b	1.34±0.29a	2.34±0.45a	1.43±0.14a	1.98±0.48a	1.62±0.22a	1.48±0.06a	0.90±0.03a	0.62±0.11a
RT	1.27±0.04a	0.88±0.12b	1.48±0.29a	1.99±0.24a	1.17±0.12a	1.76±0.33a	1.59±0.16a	1.23±0.14a	0.82±0.09a	0.82±0.06a
RT+CR	1.36±0.10a	0.96±0.08b	1.13±0.19a	2.15±0.27a	1.28±0.06a	1.73±0.18a	1.83±0.35a	1.38±0.06a	0.86±0.06a	0.70±0.10a
RT+CR+PL	1.27±0.05a	1.45±0.19a	0.94±0.14a	2.83±0.52a	1.48±0.15a	1.30±0.12a	1.95±0.35a	1.65±0.24a	0.95±0.05a	1.48±0.08a
RT+CR+PL+BC	1.61±0.09a	1.37±0.15a	0.93±0.12a	2.68±0.56a	1.72±0.14a	2.53±0.52a	2.10±0.25a	1.65±0.19a	0.98±0.16a	1.37±0.28a
	2024 After corn									
CT	1.42±0.16a	1.07±0.17b	1.19±0.20a	2.12±0.34a	1.61±0.13b	1.79±0.40a	1.70±0.34a	1.66±0.25a	0.92±0.18a	0.54±0.11b
RT	1.26±0.04a	1.18±0.12b	1.04±0.11a	2.15±0.30a	1.40±0.16b	1.84±0.29a	1.30±0.20a	1.31±0.07a	0.82±0.04a	0.40±0.07b
RT+CR	1.29±0.04a	0.98±0.09b	1.23±0.17a	2.11±0.34a	1.60±0.12b	1.91±0.40a	1.05±0.07a	1.19±0.30a	0.81±0.06a	0.66±0.08b
RT+CR+PL	1.35±0.16a	1.74±0.17a	1.14±0.19a	2.07±0.27a	2.01±0.36a	2.01±0.42a	1.83±0.38a	1.37±0.19a	0.94±0.07a	2.08±0.42a
RT+CR+PL+BC	1.34±0.16a	1.38±0.16ab	0.66±0.11a	1.63±0.15a	1.75±0.19ab	1.58±0.41a	1.64±0.21a	1.42±0.13a	0.92±0.04a	1.29±0.24ab

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

Table S5.12: Impacts of management systems on stratification ratios of organic matter and nutrients in the cotton-corn-peanut sequence in 2022, 2023, and 2024.

Management systems	Organic matter ratio	P ratio	K ratio	Mg ratio	Ca ratio	B ratio	Zn ratio	Mn ratio	Fe ratio	Cu ratio
	---------- 2022 After cotton ----------									
CT	1.10±0.09a	1.65±0.23a	0.82±0.07a	1.21±0.18a	0.94±0.05a	1.01±0.10a	2.76±0.28a	1.48±0.11a	1.75±0.24a	1.58±0.54a
RT	1.21±0.15a	1.74±0.37a	1.14±0.17a	1.26±0.34a	1.01±0.16a	1.31±0.20a	2.93±0.36a	1.59±0.06a	1.57±0.32a	0.96±0.06a
RT+CR	1.12±0.08a	1.16±0.12a	1.15±0.15a	1.63±0.24a	1.08±0.05a	1.27±0.08a	1.99±0.10a	1.31±0.10a	1.65±0.16a	0.82±0.09a
RT+CR+PL	1.08±0.03a	1.55±0.20a	1.11±0.14a	1.73±0.38a	1.05±0.13a	1.11±0.16a	2.18±0.21a	1.32±0.06a	1.41±0.27a	1.37±0.23a
RT+CR+PL+BC	1.33±0.19a	1.69±0.40a	0.87±0.12a	1.95±0.56a	1.28±0.12a	1.20±0.18a	2.96±0.70a	1.63±0.27a	1.83±0.15a	0.88±0.07a
	---------- 2023 After corn ----------									
CT	1.15±0.11a	1.73±0.46a	1.24±0.23a	1.42±0.13a	1.08±0.07a	0.99±0.10a	2.32±0.36a	1.57±0.09a	1.13±0.08a	0.40±0.11b
RT	1.08±0.15a	2.40±0.77a	0.88±0.35a	1.50±0.16a	1.15±0.11a	1.12±0.14a	2.73±0.76a	1.61±0.27a	1.11±0.17a	1.02±0.55ab
RT+CR	1.18±0.10a	1.78±0.38a	0.90±0.13a	1.74±0.28a	1.16±0.08a	1.10±0.08a	2.19±0.26a	1.42±0.12a	1.14±0.11a	0.33±0.17b
RT+CR+PL	1.16±0.04a	2.77±0.70a	1.07±0.16a	1.66±0.19a	1.17±0.02a	1.07±0.16a	3.56±0.53a	1.61±0.16a	1.19±0.12a	1.81±0.36a
RT+CR+PL+BC	1.22±0.05a	2.73±0.88a	0.87±0.15a	1.80±0.19a	1.18±0.06a	1.16±0.24a	3.55±0.65a	1.88±0.20a	1.07±0.14a	0.87±0.15ab
	---------- 2024 After peanut ----------									
CT	1.20±0.06a	1.44±0.26a	1.37±0.20a	1.52±0.21a	1.18±0.07a	1.29±0.11a	1.85±0.34a	1.54±0.14a	0.85±0.05a	0.93±0.06a
RT	1.09±0.12a	1.58±0.49a	1.47±0.43a	1.47±0.16a	0.96±0.08a	1.20±0.24a	1.70±0.48a	1.38±0.21a	0.96±0.07a	0.81±0.06a
RT+CR	1.06±0.11a	1.15±0.22a	1.08±0.17a	1.40±0.02a	0.95±0.04a	1.04±0.13a	1.22±0.16a	1.08±0.18a	1.01±0.07a	0.86±0.09a
RT+CR+PL	1.05±0.01a	1.79±0.40a	0.68±0.08a	1.44±0.15a	1.08±0.09a	1.06±0.07a	2.20±0.48a	1.86±0.28a	1.08±0.11a	1.56±0.22a
RT+CR+PL+BC	1.17±0.08a	1.69±0.32a	0.87±0.23a	1.63±0.15a	1.19±0.08a	1.19±0.21a	1.83±0.18a	1.72±0.04a	0.97±0.11a	1.32±0.16a

Within a column in each year, means not sharing any letter are significantly different using the least squares means and adjusted Sidak multiple comparisons ($p < 0.05$). Values represent the mean ± standard error. CT, conventional tillage; RT, reduced tillage; RT+CR, reduced tillage with cereal rye; RT+CR+PL, reduced tillage with cereal rye and poultry litter; RT+CR+PL+BC, reduced tillage with cereal rye, poultry litter, and biochar.

CHAPTER 6

CONCLUSIONS AND IMPLICATIONS

The dissertation highlights the individual and complementary effects of tillage, cover crops, and organic amendments on soil health and row crop productivity. The major conclusions of the dissertation include the following:

1. Chapter Two: Integrating Cover Crops and Organic Amendments to Mitigate the Limitations of Tillage on Soil Health and Cotton Productivity.
    - The conventional tillage (CT) systems showed less soil compaction compared to the strip tillage (ST) systems in 2023 after tillage operations. Also, after tillage operations in 2023, the integration of cover crops and organic amendments into ST (ST+Int) minimized soil resistance to penetration compared to ST.
    - In general, the integration of cover crops and organic amendments into CT (CT+Int) and (ST+Int) tended to increase soil respiration and organic matter within the 0-15 cm soil depth, but the effects were not consistent across years. For instance, in 2023, the ST+Int increased the soil respiration within the 0-15 cm depth by 70% compared to

ST. Also, in 2022, the CT+Int increased the organic matter within the 0-15 cm depth by 26% compared to CT.

- The various management systems had a minimal impact on cotton productivity and fiber quality. The findings indicate that the strip tillage was effective in seedbed preparation, and the differences in soil properties were not at yield-limiting levels within three years of the study. Moreover, the inorganic fertilizer applied met the nutritional needs of the crop because the additional nutrients from the animal manure did not translate into increased cotton productivity.

2. Chapter Three: Impacts of Integrated Sustainable Management Systems on Soil Biological and Chemical Properties.

    - The two-integrated (cover crop + organic amendments; CC+OA) and three-integrated (cover crop + organic amendment + reduced tillage; CC+OA+RT) systems did not significantly increase the relative abundance of Thermoleophilia, the most abundant bacterial class. Also, the CC+OA+RT tended to have lower bacterial alpha diversity (14-19% lower) compared to the other management systems. Tillage had a dominant effect on the abundance and alpha diversity of fungi. The CC+OA+RT and RT were classified into one group, while the no-sustainable system (Nss), CC, and CC+OA were classified into a separate group based on the fungi relative abundance. The Nss, CC, and CC+OA plots were managed under conventional tillage. The RT tended to have higher fungi alpha diversity (21-38% higher) compared to other management systems.

- In the third year, plots with cover CC (CC, CC+OA, d CC+OA+RT) resulted in higher soil respiration, indicating the cover crop had a dominant effect. The study revealed no significant impact of the management systems on soil organic matter, pH, and nutrients. Furthermore, the integrated sustainable management systems did not consistently improve the soil biochemical properties. This suggests that the addition of biochar to the OA plots may have masked the effect of the cover crop and the poultry litter, particularly in conservation tillage systems where organic materials are not incorporated into the soil.

3. Chapter Four: Regenerative Agricultural Practices in Row Crop Production: Impacts on Productivity, Quality, and Nutrient Uptake.
   - The management systems had a minimal impact on row crop productivity and quality. In 2021, cotton lint and cottonseed yields increased under both reduced tillage with cereal rye and poultry litter (RT+CR+PL) and reduced tillage with cereal rye, poultry litter, and biochar (RT+CR+PL+BC) compared to the other management systems. However, only cottonseed yield showed a significant difference. The RT+CR+PL had 12-24% higher cottonseed yield than the conventional tillage (CT), RT, and RT+CR. Similarly, the cottonseed yield for RT+CR+PL+BC was 10-22% higher than the CT, RT, and RT+CR. The RT+CR+PL tended to increase lint yield and cottonseed yield in 2022 and 2023 compared to RT+CR. This indicates that the additional nutrients supplied by the poultry litter in 2021 and 2022 translated into an increase in cotton

yield. Moreover, the yield increase in 2023 suggests that the nutrients from only the poultry litter were sufficient for cotton. In contrast, RT+CR+PL+BC tended to decrease cotton yields compared to RT+CR+PL. This suggests that the high carbon-nitrogen ratio of the biochar may have led to nutrient immobilization at the early vegetative stage and subsequently declining cotton yields.

- The RT+CR+PL and RT+CR+PL+BC increased peanut biomass in 2022, but the higher accumulation of biomass did not translate into an increase in yield. Reduced tillage produced similar cotton, peanut, and corn yields as conventional tillage, suggesting that strip tillage effectively prepared the seedbed. The RT+CR+PL and RT+CR+PL+BC tended to have enriched Cu and Mo in peanut seed and hull. Also, differences in the nutrient uptake in crop biomass, particularly corn and peanut, did not translate into an increase in crop yield.

4. Chapter Five: Complementary Effects of Reduced Tillage, Cereal Rye, and Organic Amendments on Soil Health in Row Crop Production Systems.

    - The management systems had no impact on the soil physical indicators except the SRP. Generally, when averaged across all the management systems, the SRP increased with depth. Also, in several instances, all the management systems showed compaction beyond the 15 cm soil depth in all crop sequences. The VWC was low (less than 0.15 $cm^3\ cm^{-3}$) in most cases, indicating the soil was not at field capacity. Where there were significant differences, the SRP tended to be lower in the conventional tillage and/or reduced tillage (RT) compared to the other management systems.

- Soil respiration and organic matter did not differ significantly by the management systems. When averaged across all the management systems, the soil respiration and soil organic matter were higher within the 0-15 cm soil depth, suggesting more food substrate and microbial activity. The addition of poultry litter in reduced tillage and cereal rye (RT+CR+PL) tended to increase the concentrations of Mehlich-I extractable P, Zn, Mn, and Cu. Overall, integrating reduced tillage, cereal rye, poultry litter, and biochar did not substantially improve soil health.