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Soil health as influenced by the integration of cover crops and poultry litter in north-central Mississippi

Nikitha Reddy Kovvuri
Mississippi State University, nk587@msstate.edu

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By

Nikitha Reddy Kovvuri

Approved by:

Guihong Bi (Major Professor)
Gary Feng (Director of Thesis)
Johnie N. Jenkins (Committee Member)
K. Raja Reddy (Committee Member)
Nuwan K. Wijewardane (Committee Member)
Michael S. Cox (Graduate Coordinator)
Scott T. Willard (Dean, College of Agriculture and Life Sciences)

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Name: Nikitha Reddy Kovvuri

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Institution: Mississippi State University

Major Field: Horticulture

Major Professors: Guihong Bi and Gary Feng

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Candidate for Degree of Master of Science

Soil health-based agricultural management practices are widely promoted to improve soil structure, infiltration and reduce erosion. This study was conducted at two locations in North-Central Mississippi to evaluate the influence of different cover crop species and poultry litter on soil health that can impact crop production, climate change, and resilience. The results indicated that the cover crops showed a little effect on some soil health indicators compared to control treatment. However, in one location, rye, and a mixture of cover crops decreased bulk density and increased available water content and organic matter. The poultry litter had a positive effect on most soil physical and chemical health indicators. The cover crop species at Pontotoc decreased bulk density, increased field capacity, CEC, and total carbon. However, there was no significant effect of cover crops on most soil chemical health indicators, and soil responses may take more than five years for the changes to appear.

DEDICATION

I would like to dedicate this work to my parents, Uma Kovvuri & Narendar Reddy Kovvuri. Thank you for everything you did for me, none of this would have been possible without your love and support. I would dedicate this work to my brother Akhil Reddy Kovvuri for his love, encouragement and constant guidance whenever needed. I would like to dedicate this thesis to my partner and best friend, Srikanth Reddy, for always being there for me and for his belief in me. Lastly, I dedicate this work to all my friends, who were my reason to smile and gave me unconditional love and moral support while I was away from home.

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CHAPTER I

LITERATURE REVIEW

Cover Crops

Increasing crop productivity to substantiate the hunger of the rapidly growing world's population has led to the use of agricultural practices leaving an environmental footprint in the ecosystem. To maintain ecological sustainability and improve crop productivity without compromising our environment is the biggest challenge we face today. One of the best conservation practices is the integration of cover crops in Agro-Systems which are well known for the benefits like soil & water conservation and weed management. Historically, to retain soil organic matter and nutrients, crop residues served the purpose of mulch as a soil and water conservation practice. Cover crops are defined as any non-cash crops grown primarily to cover the soil for erosion control and recognized as one of the strategies adapted by farmers to maintain a balance between the crop production, soil health, and sustainability (Nouri et al., 2019a). The integration of cover crops have been known to reduce the susceptibility of soils to erosion and leaching as they contribute to residue accumulation leading to high crop yields (Nouri et al., 2018). To enhance soil properties, cover crops have been first introduced in China over 3,000 years ago (Burket et al., 1997). Later, in North and South America, legumes, vetch, and lupins gained importance as cover crops in the nineteenth century and has encouraged many farmers to grow cover crops as an alternative management practice (Groff, 2015). The emerging trend of growing cover crops between crop production cycles has resulted in the establishment of the

Sustainable Agriculture and Research Education program by USDA in the year 1991 to promote the research in cover crops.

Planting cover crops after the termination of the primary cash crop in the fall and allowing them to grow until spring is a common practice adapted in most of the southeastern United States. The proper selection and use of cover crops have been proved to maximize nutrient availability, reduce nitrogen (N) leaching losses and improve soil organic matter (Adeli et al., 2011). In general, cover crops are classified into three categories such as leguminous, grasses, and non-leguminous broad leaves based on taxonomy and each of them offer different ecosystem services. Cover crops like hairy vetch, field peas, clover and beans fall into the leguminous category. These species can fix atmospheric nitrogen facilitating less usage of nitrogen fertilizer inputs for following cash crops by providing 50- 150 pounds per acre of nitrogen (Clark, 2019). The biomass produced from legumes is utilized as crop residue that enhances the nutrients, organic carbon and nutrients in soil which is beneficial to the subsequent crop (Lüscher et al., 2014; Olson et al., 2014). In addition, the inclusion of legumes in the cover crops has reportedly increased the yield of the following crop by an average of 13% (Weiner et al., 2010). Studies showed that the residue and biomass accumulation after the use of legumes for several years has positive influence on soil's physical and chemical characteristics resulting in improved soil structure, increased organic matter, soil water holding capacity, stable aggregates and nitrogen content (García-González et al., 2018; Tiemann et al., 2015; Villamil et al., 2006). The legume cover crops has the potential to influence soil strength, hydraulic characteristics by improving the soil structure and texture (Oliveira et al., 2019). Furthermore, the residues from legume cover crops can suppress weeds as they can reduce the light intervention that can regulate the soil temperature (Khaliq et al., 2015; Gallandt et al., 2005). Soil temperature can play a key role in inhibition of weeds as the seed dormancy is highly dependent on light and temperature (Fahad et al., 2015; Mirsky et al., 2011; Teasdale and Mohler, 1993). Such studies have also been evidently reported by (Ranaivoson et al., 2017) who stated that limited light transmission on the soil surface was noticed with the integration of legumes resulting in inhibition of weed emergence. Several other soil related benefits can be retrieved with the use of cover crops like oat, barley, cereal rye, forage grasses and winter wheat that belong to grasses. A seven year study by Basche et al., (2016) revealed that the winter rye cover crop has potentially increased the soil water holding capacity by 10 - 11 % and the plant available water content by 21 – 22%. Cover crops when integrated on to the soil surface can enable reduced intensity of rainfall tricking into slow movement of water droplets into the soil surface enhancing the water infiltration rate which ultimately increased the soil water storage capacity (Sammis et al., 2012; Sharma et al., 2012; Joyce et al., 2002). Studies have shown that the non-legume crops have the ability to reduce nutrient leaching especially nitrogen for the following crop by inhibiting the nitrate leaching from the soil profile (Gabriel et al., 2013). Similar results were observed from studies conducted by Kaspar et al., (2012); Bergström and Jokela et al., (2001) who evaluated the effectiveness of cover crops like rye grass and oats on reduced nitrate leaching concentrations by 48 % and 26 % respectively. Furthermore, there was 70 % lower nitrate leaching in the soils integrated with non-legume cover crops when compared to bare fallow systems (Tonitto et al., 2006). A long-term cover crop study that was initiated to understand the impact of winter cover crops such as rye and oats resulted in increased soil organic carbon under corn and soybean crop rotation system (Kaspar et al., 2006). Another major category of cover crops that constitutes cover crops such as brassicas, mustards, buckwheat, and phacelia is non-leguminous broadleaves. It is reported that broadleaf species can be more favorable in releasing captured nutrients than grasses and their deep tap root system facilitates less soil compaction and improved soil structure (Koudahe et al., 2022). In some instances, these cover crops have reportedly increased the available phosphorus content and when combined with manure promoted better nutrient management (Cottney et al., 2020; White et al., 2016; Thilakarathna et al., 2015).

Several studies have shown that cover crops can retain soil moisture by reducing water loss as it acts as a ground cover (Blanco-Canqui and Ruis et al., 2020). In addition, cover crops aid in improving the soil structure, high water infiltration and stable aggregates over a certain period. Along with this, they can also regulate the soil temperature and water content under severe climatic conditions (C. Kahimba et al., 2008). However, a few studies have shown that there can be very little or no changes in the soil properties like organic matter, bulk density, total carbon, and total nitrogen with the integration of cover crops (Rorick and Kladivko et al., 2017) and several other studies have reported that use of different cover crops could improve soil health by improving the soil properties like organic matter, hydraulic conductivity, ability to hold water, water infiltration, nutrient availability, nitrogen content after a few years (Haruna et al., 2020). A few studies have indicated that multispecies cover cropping has potential benefits as compared with a single species or no cover crop (Franzluebbers et al., 2021). Cover crops, when integrated into the cropping systems, aid in efficient usage of available nitrogen to the following crops by reducing the leaching losses while enhancing the soil moisture content to restore the soil health (Adeli et al., 2019). A 34-year long-term cover crop study in southeastern US has witnessed increased infiltration rate, saturated hydraulic conductivity, mean weight diameter of aggregates when integrated with vetch cover crop under no-tillage conditions (Nouri et al., 2019a). Similar results were reported in a 17 year no-tillage cover crop study, where rye, vetch and clover cover crops increased water retention in soil, saturated hydraulic conductivity when compared to fallow soils with no cover crop treatment.

Poultry Litter

The poultry industry is one of the most rapidly expanding agro-based industries in the United States. The total broiler production in the US accounted for almost 9.6 billion birds (USDA, 2021). Mississippi has about 1,900 poultry farms producing 707 million broilers per year. This has led the poultry industry to stand as the largest agricultural commodity of the state (USDA, 2021). Studies have reported that about 44.4 million tons of poultry litter (PL) have been produced in the US containing 2.2 million tons of N, 0.7 million tons of Phosphorous (P) and 1.4 million tons of Potassium (K) in the year 2008 (MacDonald et al., 2009). Mississippi, being the fifth largest broiler-producing state, is generating 1.1 million Mg of poultry litter every year with a nutrient composition of 32 kg N per ton, 21.5 kg K_2O per ton, and 27.5 kg P_2O_5 per ton (Zhang et al., 2013).

Poultry (*Gallus gallus domesticus)* litter is a mixture of poultry manure, spilled feed, feathers, and bedding materials that is a valuable source of plant nutrients such as N, P, K, and trace elements such as Copper (Cu), Zinc (Zn), Manganese (Mn), and Boron (B), and organic matter (Tasistro et al., 2004). In addition to providing plant nutrients, poultry litter application acts as a soil amendment to improve soil properties such as water holding capacity, cation exchange capacity, soil tilth, soil fertility, and soil reaction (pH). Intensive agricultural practices have led to the degeneration of soil which ultimately affects crop production. It has been reported by (Pahalvi et al., 2021) that inorganic fertilizers do not show any response on degraded soils. Henceforth, organic manures have gained the most attention in recent years to help intensify the crop productivity while improving soil health which are a cost effective management practice

(Neemisha and Rani, 2022). Poultry litter is identified as one of the inexpensive fertilizer to increase crop productivity and maintain soil health simultaneously (Harmel et al., 2011; He et al., 2009; Beavis and Mott, 1996). In addition to providing many nutrients to row crops, litter can also benefit soil health by increasing the soil organic matter (Bolan et al., 2010). Studies conducted by Liu et al., (2009); Li and Zhang, (2007); Ludwig et al., (2007) have reported that farmyard manures can potentially benefit certain soil properties further promoting the reduction of inorganic fertilizer usage and to improve long-term sustainability by optimizing nutrient management. It also ameliorates water retention in soil by reducing the soil compaction and improved soil structure (Motavalli et al., 2003). Along with this, it is shown that poultry manure application to the soil has improved the organic matter and aggregate stability which resulted in improved fertility content of soil (Cayci et al., 2017).

However, there have been many counter effects with the use of PL as it has a potential role in increasing eutrophication and P runoff (Sharpley et al., 2009). According to Mississippi's Dry Litter Poultry General Permit, there is a need to perform soil analysis for P content once every 5 years and PL must be analyzed for N and P content on an annual basis to prevent the excess nutrient leaching in the soil which can lead to long-term environmental pollution (Tabler et al., 2015). In general, the broiler litter availability is synchronous with the crop demands, as the manure applications occur after the crop harvest in fall and growers are primarily interested in PL given the advantages of manure and its potential to reduce fertilizer inputs in the following season (Seman-Varner et al., 2017). In most southeastern US, poultry litter is often combined with other management practices such as no-tillage and cover crop use that has resulted in increased soil organic matter and greater crop yields (Cavigelli et al., 2018; Tewolde et al., 2018; Sainju et al., 2008). Previous studies conducted by Ashworth et al., (2017) stated that soils amended with broiler litter (Holatko et al., 2022) altered the soil pH, nutrient availability which increased the microbial activity. Further, a 12 year long-term study was conducted by Ashworth et al., (2018) to evaluate the influence of litter and crop rotations which resulted in greater soil pH, K, Magnesium (Mg), Calcium (Ca), nitrogen content, carbon content compared to control treatments. This study has also suggested that manure applied soils had greater soil fertility levels and high soil biodiversity as compared to other management practices. Studies have evidently shown that broiler litter application can help in reducing the soil erosion by acting as mulch layer and is known to provide essential nutrients to the crops along with conserving the soil water content and increasing the organic matter in the soil (Adeli et al., 2019). In addition to this, Adeli et al., (2019) also observed a 19% increase in total carbon content in litter applied soils compared to no fertilizer treatment in a 3 year study period. Broiler litter, being one of the cost effective fertilizer is considered an effective source of nitrogen and phosphorus content (Holatko et al., 2022), has reportedly supplemented the phosphorus requirement of the soybean crop in a study conducted by (Toor, 2009). The organic N in the broiler litter is available to the crop in a mineralized form and hence it is considered a slow-releasing fertilizer as it aids in fulfilling the crop N requirements during the peak growing stages (Gaspar et al., 2017; Salvagiotti et al., 2008). A study by Espinoza et al., (2007) in Arkansas has reported similar results indicating that more than 90 % of N being in an organic form, it takes time to be available for the plant uptake whereas phosphorus and potassium nutrients are available for the plant uptake forthwith making poultry litter a potential source of these nutrients for crop production. Previous research by (Adeli et al., 2009) has reported that poultry litter application increased available phosphorus and nitrate-nitrogen concentration in the topsoil (0-5 cm). Pokhrel et al., (2021) observed an increased total nitrogen content by 11% with poultry litter application and these results were similar to a study conducted by (Lin et al., 2019) in northeast Alabama, who reported greater nitrogen accumulation in soils amended with litter. Further, another 4 year study by (Parker et al., 2002) that was conducted in Alabama reported increased total carbon content with the integration of poultry litter and also suggesting a necessary long-term evaluation on management practices to see a difference within treatments.

Soil Health

Soil is a thin layer of covering on the surface of the earth that serves as a major association between the environment and agriculture. It is known as an essential link in the cycle of life, being a critical component of food and water security as it plays a crucial role in recycling nutrients, regulation of water flow and providing a medium for plant growth (Doran and Parkin, 1994). The current agricultural practices and continuous crop production has resulted in depletion of soil quality, eroded soil, and reduction in organic matter. We are challenged to develop sustainable conservation practices which can help preserve agriculture for the upcoming generations without compromising our environment. Soil health is defined as the potential of soil to function as an important living biome that sustains plants, animals, and humans by maintaining the environmental quality (Doran and Parkin, 1994). One of the critical indicators of sustainable management is soil health or quality. Soil being the interface between environment and agriculture is considered as one of the driving forces that can maintain the ecological balance. The quality of soil or soil health can be determined using several indicators associated with physical, chemical, and biological properties of soil (Singh, 2020).

The importance of assessing the indicators of soil health to promote soil quality by following management practices have been explained by (Doran and Parkin, 1994). Due to intensive agricultural practices, soil physical, chemical, and biological properties undergo changes which may be detrimental to the living ecosystem. To assess soil health, certain soil health indicators have been selected which represent the soil function and help to achieve a soil health score (Cole, 2018; Vasconcellos et al., 2013). There are several soil health assessment methods that have been followed by farmers, conservationists, and soil scientists which includes Soil Management Assessment Framework (SMAF), Comprehensive Assessment of Soil Health (CASH), Ontario Soil Health Assessment (OSHA), Alabama Soil Health Index (ASHI), and Haney's Soil Health Test (HSHT). Each of these soil health assessment methods has its own advantages and limitations. For soil health assessment, Standard Scoring Function (SSF) based curves are developed based on different classic mathematical models like Principal Component Analysis (PCA), Analytic Hierarchy Process (AHP), The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method based on the Entropy weight method can be used to normalize the data. To acquire the most optimum and consistent results, different soil health assessment approaches can be modified or combined based on the local climatic and soil conditions (Chang et al., 2022).

Soil Health Indicators

Soil health assessment can be done with suitable soil indicators that can be considered to evaluate the soil health. Several soil degradation issues have been addressed by Cornell Soil Health Team to establish a protocol for rejuvenation of soil health. The Cornell Comprehensive Assessment of Soil Health (CASH) has emphasized 42 potential soil health indicators that are used to evaluate the soil health as a report which has been utilized by many producers, agricultural consultants and prioritize the soils that need management practices. According to Cornell Soil Health Institute, there are some fundamental soil health indicators that are used to assess the soil health such as bulk density, saturated hydraulic conductivity, available water content, available phosphorus, potassium, pH, nitrogen content, total carbon, and cation exchange capacity (Moebius-Clune et al., 2016). To interpret the soil health indicators, scoring functions for each indicator were developed and these values were assigned scores between 0 and 100 to assess the soil health (Andrews et al., 2004).

Soil bulk density

Soil texture is one of the significant contributors to understand the soil health as it is associated with compaction, erosion, infiltration rate, and porosity (Cardoso et al., 2013; Schoenholtz et al., 2000). Soil bulk density, an indicator of soil compaction, is considered a crucial factor of soil moisture content as it can vary with soil structure and texture (Han et al., 2016; Yang et al.,2016). It is reported that bulk density is an essential characteristic of soil physical and chemical properties (Han et al., 2017; Casanova et al., 2016; Moret-Fernández et al., 2016). It is well documented that the dryness of the soil will lead to deformation of soil structure making the soil more susceptible to compaction and erosion (Batey, 2009). Several studies have confirmed that the bulk density of soil is correlated with the soil water content, which is the most influencing factor for crop production and soil health (Shah et al., 2017).

Saturated hydraulic conductivity (Ksat)

Soil hydraulic properties are fundamental for elucidating the relationship between soil surface water and energy balance by regulating water through infiltration capacity of soil, runoff, erosion and evapotranspiration (Zhang and Schaap et al., 2019; Montzka et al., 2017). Saturated hydraulic conductivity (Ksat) is one such parameter that determines the flow rate of water, especially rainwater, within the soil profile. Researchers like Mwendera and Feyen, (1993) have suggested that Ksat can decrease when the compaction is too high in the soil which is associated with higher bulk density. Several agricultural operations have made the soils susceptible to compaction, run off and reduced soil strength (Fabrizzi et al., 2005). Most studies on soil physical and chemical health indicators have revealed that soils with high Ksat, higher infiltration rate and lower bulk density are considered to be healthier (Miriti et al., 2013; Gicheru et al., 2004; Lampurlanés and Cantero-Martínez et al., 2003).

Soil water retention

Healthy soils are critical to sustain plant and animal life, and in recent years several management strategies have been introduced to improve soil quality, maintain high crop productivity and achieve the goal of long-term sustainability in modern agriculture (Nouri et al., 2019a). Water retention in soil is considered one of the important soil hydraulic health indicators that correlates to soil water content pertaining to crop yields (Turmel et al., 2015). Soil water retention parameters are described as the water holding capacity of a soil profile, wilting point, and the plant available water content. The water holding capacity of a soil is the amount of water held by soil after the soil loses its gravitational water. It can also be denoted as field capacity which is determined at the pressure head 33 kPa. The permanent wilting point, determined at the pressure head 1500 kPa of a soil is the stage of a soil where the plant can no longer uptake any water from the soil leaving the plant to wilt and ultimately die. The plant available water content of a soil is the difference between the water holding capacity of a soil and the permanent wilting point, where the crop can utilize the water available in the soil pores (Tsang and Ok, 2022). It is important to understand the relationship between the soil moisture content and the water potential determined at different pressure heads as it plays a key role in predicting the soil water storage and water availability for plant uptake (Panagea et al., 2021). Soil texture and soil structure are the major influencing characteristics on soil water retention, where the soils with higher bulk density has lower soil moisture content, less porosity that affects the plant growth (Ochsner, 2019).

Soil pH

Assessment of soil health in terms of chemical parameters can be challenging, as there is a need to optimize various health indicators which are necessary for maintaining the soil quality (Marschner, 2011). Soil pH can influence the soil sustainability and ecosystem attributes and hence is proposed as one of the potential health indicators (Rengel, 2011). Soil pH can be interdependent with nutrient dynamics in the soil profile and the extraction methods used to determine the nutrient concentrations such as K, Mg, Ca, Na, Fe, Zn and Mn can vary with the pH value (Norris et al., 2020).

Other soil chemical health indicators

Several soil chemical health indicators meet the criteria to be considered for the soil health evaluation according to CASH (Cornell's Comprehensive Assessment of Soil Health) but interpreting and quantification of these indicators can be sensitive as they depend on soil texture, climate and nutrient management (Doran and Zeiss, 2000). Chemical indicators like total carbon and organic matter can be interdependent on soil texture, mineralization of carbon by microbes and nutrient cycling (Lavallee et al., 2020). It is strongly believed that organic amendments applications can increase the organic matter of soil and can be considered as one of the critical soil health indicators (Liptzin et al., 2022). Further, it is shown that cation exchange capacity of soil tends to increase with increase in organic matter of soil (Rayne and Aula et al., 2020). Integrating soils with different cover crops and animal manure can potentially increase the nutrient availability that can be utilized for crop production. In addition to this, nitrate leaching can be reduced with manure application resulting in more plant-available nitrogen (Rayne and Aula et al., 2020). It is also reported that poultry litter has the highest concentrations of Phosphorus (P) as compared to other animal manures, and trace elements like Zn, Cu and Mn accumulation are positively associated with the P content in the soil (Steiner et al., 2007).

CHAPTER II

EFFECT OF DIFFERENT COVER CROP SPECIES AND POULTRY LITTER APPLICATIONS ON SOIL PHYSICAL AND SOIL CHEMICAL HEALTH

Abstract

The soils in the Southeastern United States are prone to run-off, compaction, and degraded soil health due to intensive farming practices. Soil health based sustainable management practices are widely promoted to improve soil structure, infiltration and reduce erosion. The integration of Cover Crops (CC) and Poultry Litter (PL) into existing cropping systems could potentially improve soil properties in this region. However, the studies on CC and PL on soil physical and soil chemical health indicators contributing to soil health are limited. A field experiment was conducted to evaluate the influence of different cover crop species and fertilizer treatments on soil physical and chemical properties that could improve soil health on a fine, silty loam soil in the Pontotoc Ridge-Flatwoods Branch Experiment Station from fall 2017 to 2022. The experimental design was a randomized complete block with split structure of two factors (cover crop and fertilizer) replicated four times. The cover crop treatments included cereal rye, hairy vetch, winter wheat, mustard, and cereal rye (CC-mix), and native vegetation (control). The three fertilizer treatments included poultry litter, inorganic fertilizer (phosphorus, potassium, and elemental sulfur), and no fertilizer. Soil properties were measured at 0-5 and 5-10 cm depth and the results indicated that PL amended soils as compared to control plots increased calcium, cation exchange capacity, total carbon, magnesium, plant available water, potassium,

and saturated hydraulic conductivity by 4.4%, 11%, 16%, 27.06%, 27%, 47% and 300% respectively. As compared to no fertilizer plots, PL amended plots decreased the bulk density by 5%. Cover crops like cereal rye, mustard, and cereal rye (mix) increased the total carbon content by 3.4% and 14.5% respectively and vetch increased the CEC by 15.9% as compared to native vegetation (control). Although some soil health indicators were not influenced by the management practices, our results showed that the PL amended soils resulted in improved soil physical and chemical health as compared to other fertilizer treatments.

Introduction

Sustainability in agriculture is the ability of agrosystems to provide without leaving an environmental footprint (Edwards, 2020). Cover cropping has been one of the best farm management practices that has been adopted by many producers across the world that aids in crop production while providing several soil benefits. Cover crops have been found to enhance soil properties, nutrient cycling, weed suppression and reduce soil run-off (Saleem et al., 2020). Furthermore, a study by Norris and Congreves, (2018) reported that soil health may be rejuvenated with the integration of cover crops across different climatic zones. The main purpose of cover crop introduction into cropping systems is to cover the soil and establishing a soil-plant-microbial dynamics facilitating crop production and regenerating soil systems (Husson et al., 2021). A recent study by Wood and Bowman, (2021) revealed that cover crops had a positive impact on soil health indicators after 5 years of cover crop use. Cover crop integration into a no-tillage system can potentially increase soil organic carbon and maintain soil health (Balota et al., 2014). However, the potential benefits of cover crops will be dependent on several factors such as soil type, climatic conditions, tillage practices, crop rotation and nutrient management (Poeplau and Don, 2014).

Soil health is conceptualized as the integration of physical, chemical and biological aspects of soil which can be analyzed with several soil health indicators (Lehmann et al., 2020). Continuous intensive agricultural practices, excessive use of chemical fertilizers, tillage practices and climate change have led to soil health degradation. Degraded soils are susceptible to high soil erosion, soil compaction, low organic matter, high soil run-off making the soil unfit for crop production. Focusing on soil health is the foundation of productive, sustainable agriculture. Soil health can be achieved by managing physico-chemical soil properties and in addition, promoting soil microbial communities can be possible by employing organic amendments which are known to increase the organic matter leading to improved crop production and resilience (Karlen et al., 2019). Poultry litter is one such cost effective environmentally friendly amendment that has been introduced to rejuvenate soil health. Poultry litter is an exceptional source of nutrients such as organic nitrogen, phosphorus, potassium, sulfur, and other micronutrients that help in increasing the crop productivity as compared to other fertilizer sources (Seidavi et al., 2021; Garg and Bahl, 2008). Several studies have alluded to the fact that poultry litter application can improve soil organic matter, soil water holding capacity, cation exchange capacity and promote conservation of soil moisture by retaining substantial amounts of soil water content (Sushkova et al., 2021; Amanullah et al., 2010; Bauer and Black, 1992). Eusufzai and Fujii, (2012) reported that organic amendments have a positive influence on the soil physical and hydraulic properties like bulk density and saturated hydraulic conductivity.

This study evaluated the effects of different cover crop species and poultry litter on soil physical, hydraulic, and chemical properties in a no-tillage dryland system. The selected cover crops included cereal rye, hairy vetch, winter wheat, and mustard and cereal rye (CC-mix). Many studies have previously focused on the influence of poultry manure and cover crops species on soil physical and chemical characteristics but there is a need to understand the impact of interaction of these management practices on soil health.

Materials and Methods

Study Site

A cover crop study was conducted at the Pontotoc Ridge-Flatwoods Branch Experiment Station in Pontotoc County, MS (34˚07′ N, 88˚59′ W) (Figure 2.1). The study was initiated in October 2017 and carried out through October 2022. The soil series at the study site was an Atwood silt loam (fine-silty, mixed, semi-active, thermic Typic Paleudalfs) on a 3% slope. The study was conducted under no-tillage, rainfed conditions.

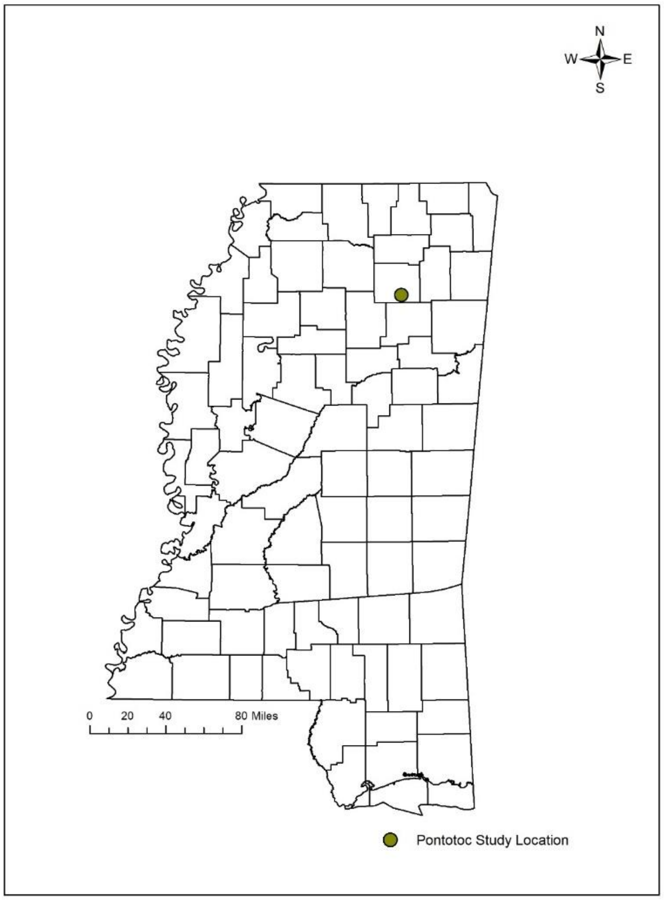

Figure 2.1 Study location (Pontotoc Ridge-Flatwoods Branch Experiment Station, Pontotoc County) in the map of Mississippi.

Experimental Design

The experimental design was randomized complete block design with a split-plot treatment structure of two factors and four replications. Cover crop with five levels was the main plot factor and fertilizer source with three levels was the sub-plot factor. Each replication consisted of fifteen whole plots 167.2 m^2 (1800 $ft.^2$) each and 45 sub-plots 74.4 m^2 (800 $ft.^2$) each. The five cover crop treatments included cereal rye (*Secale cereale*), hairy vetch (*Vicia villosa*), winter wheat (*Triticum aestivum*), mustard (*Brassica rapa*) and cereal rye (CC-mix), and native vegetation (control). The three fertilizer treatments included poultry litter, inorganic fertilizer (phosphorus, potassium, and elemental sulfur), and no fertilizer.

Field Methods

The cover crop type, rate of application, date of planting and dates of termination from the year 2017 till 2022 were summarized in the Table 2.1. Cover crops were terminated with glyphosate + dicamba in 2018 and 2019 and with roundup + dicamba in the years 2020, 2021, and 2022. Fertilizer sources included poultry litter and inorganic fertilizer. Inorganic fertilizer rates were based on soil test recommendation from Southern Soil Labs in Yazoo City, MS. Poultry litter application was based on an equivalent amount of P_2O_5 as inorganic fertilizer. The analysis of poultry litter was conducted by the nutrient analysis laboratory, USDA-ARS at Mississippi State, MS. The recommended fertilizer rates were P_2O_5 at 134.5 kg ha^{-1} (120 lb ac^{-1}), K_2O at 33.63 kg ha^{-1} (30 lb ac^{-1}), and S at 22.42 kg ha^{-1} (20 lb ac^{-1}) based on the Lancaster macronutrient extraction method. Phosphorus was applied as triple superphosphate at 292.5 kg ha^{-1} (261 lb ac^{-1}). Potassium was applied at 56.04 kg ha^{-1} (50 lb ac-1) as muriate of potash. Sulfur was applied as 90% elemental S at 24.7 kg ha^{-1} (22.2 lb ac^{-1}). Poultry litter was surface broadcasted at 4695.3 kg ha^{-1} (4189 lb ac^{-1}) in 2018 and 4483.4 kg ha^{-1} (4000 lb ac^{-1}) in 2019 till 2022. Each plot was treated with the same treatment each year.

Table 2.1 Cover crop treatments, rates applied, dates of planting and termination.

Year	Cover crop type	Cover crop rate (Kg ha^{-1})	Date of planting	Date of termination
2017	Cereal Rye	91.91	10/30/2017	04/19/2018
	Vetch	22.42		
	Cereal rye and mustard (mix)	16.81		
	Winter Wheat	94.15		
2018	Cereal Rye	91.91	10/29/2018	04/17/2019
	Vetch	22.42		
	Cereal rye and mustard (mix)	16.81		
	Winter Wheat	94.15		
2019	Cereal Rye	91.91	11/05/2019	04/17/2020
	Vetch	22.42		
	Cereal rye and mustard (mix)	16.81		
	Winter Wheat	94.15		
2020	Cereal Rye	91.91	10/15/2020	04/15/2021
	Vetch	22.42		
	Cereal rye and mustard (mix)	16.81		
	Winter Wheat	94.15		
2021	Cereal Rye	91.91	10/27/2021	04/20/2022
	Vetch	22.42		
	Cereal rye and mustard (mix)	16.81		
	Winter Wheat	94.15		

Soil Sampling and Preparation

The soil samples at the study site Pontotoc Ridge-Flatwoods Branch Experiment Station were collected from each plot at depths of 0-5 and 5-10 cm (Figure 2.2). Core soil sampling was done in each plot at depths of 0-5 and 5-10 cm. 560 undisturbed core samples were collected in total at depths 0-5 and 5-10 cm. Along with this, we have collected soil samples from 4 randomly selected native vegetation plots near the experiment site. We have also collected 180 disturbed soil samples at depths of 0-5 and 5-10 cm. For long-term storage, samples were kept in the refrigerator upon arrival in the laboratory.

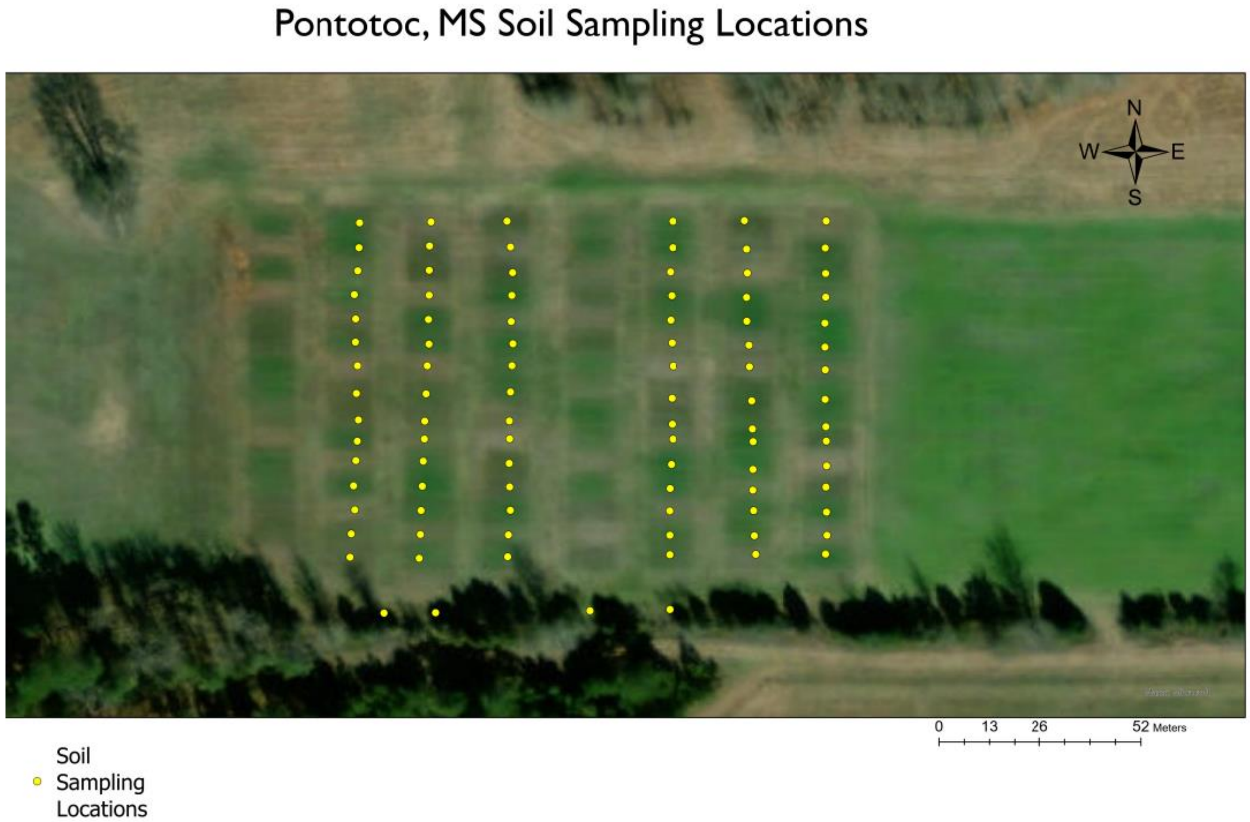

Figure 2.2 Soil sampling points in the study site (Pontotoc Ridge-Flatwoods Branch Experiment Station, Pontotoc County, MS)

Soil Physical Health Indicators

Soil bulk density

The soil bulk density is an indicator of soil compaction and to determine the impact of cover crops on bulk density, we used centrifuge core soil samples with an inner ring diameter of 5.7 cm and length of 5 cm stainless steel core rings. The core ring was pushed into the soil and any excess soil was trimmed from both the edges of the ring. The fresh weight of soil with the ring was recorded first and then was run at different RPMs from 300 till 10000 in a refrigerated high-speed centrifuge and the core rings with the samples were dried at 105 ^{0}C in an oven for 24 hours after recording the weight at 10000 RPM. The dried soil weight was then recorded, and the bulk density is calculated as the dried mass of the soil divided by the volume of the soil.

$$\text{Bulk density} = \frac{\text{Oven dried mass of soil (g)}}{\text{Total volume (cm3)}} \tag{2.1}$$

Saturated hydraulic conductivity (Ksat)

To understand the influence of cover crops on saturated hydraulic conductivity, a constant-head method by Chameleon Automated Ksat 2816, which has the 5 station Chameleon Kit (Soilmoisture Equipment Corporation (SEC) 2816GX) was used to obtain measurements. The soil samples were set to saturation for 24 hours before the start of each measurement. Ksat data is generated by precision pressure transducers and the Chameleon Software Application which monitored the pressure head and steady-rate flow over time.

Using Darcy's law (Darcy, 1856), Ksat is estimated by the following equation,

$$K = \left[\frac{aL}{A(t_0 - t_1)}\right] \ln\left(\frac{h_0}{h_1}\right) \tag{2.2}$$

Where, K = saturated hydraulic conductivity ($cm.min^{-1}$);

Q = discharge (cm^3);

$h_0 - h_1$ = difference in hydraulic head;

$t_0 - t_1$ = time difference during which $h_0 - h_1$ occurred (min/ hr);

A = cross-sectional area of the sample (cm^2);

L = length of the soil sample (cm).

Soil water retention

The soil water retention parameters such as soil water holding capacity, permanent wilting point and plant available water content were determined using a CR22 N High-Speed Refrigerated Centrifuge (Hitachi, Tokyo, Japan), one of the widely recognized methods to determine the water retention in soil (Reatto et al., 2008 ; Khanzode et al., 2002). The water content at the pressure heads (H=336, H=15310) are calculated by running the centrifuge at different rotations per minute like 300, 650, 850, 950, 1000, 1350, 7000, 9000 and 10000. The mass and the soil compression height of the soil samples were monitored after each RPM and kept in the oven for drying at 105 ^{o} C for at least 24 hours and the obtained dry weights of the samples will be recorded to know the water held by the soil at the desired water potential levels (Feng et al., 2019a). The conversion formula of centrifuge speed and soil pressure head (H).

$$\mathrm{H} = 1.398\mathrm{x}10 - 6\mathrm{n}2[\mathrm{r} - (\mathrm{l} + \mathrm{h})](3\mathrm{r} + \mathrm{l} + \mathrm{h}) \quad (2.3)$$

Where, H = The corresponding soil suction value at a certain speed (cm);

n = centrifuge speed (r/min);

r = Rotation radius from the centrifuge axis to the bottom of the soil sample (cm);

l = The distance from the centrifuge shaft to the top of the centrifuge box cover (cm);

h = Soil compression height (cm).

The water retention parameters are derived by fitting the obtained parameters into the MATLAB software developed by Van Genuchten (1980). The van Genuchten model is widely used to describe the relationship between volumetric water content (θ_v) and soil water pressure head (ψ).

$$\theta(\psi) = \theta\mathrm{r} + (\theta\mathrm{s} - \theta\mathrm{r})/[1 + (\alpha|\psi|)\mathrm{n}]\mathrm{m} \quad (2.4)$$

where θs is the saturated volumetric water content, θr is the residual volumetric water content, α is an empirical parameter, which is the inverse of the air entry point or bubbling pressure (cm^{-1}); and *n* is an empirical constant that affects the curve shape (Van Genuchten, 1980; Yates et al., 1992).

Soil Chemical Health Indicators

Soil pH

The soil pH was measured on soil: water (1:1) slurry following the procedure by (Thomas, 1996). Ten grams of air-dried soil sample was weighed into a 50 mL beaker. Ten mL of deionized water was added and mixed well. The soil suspension was allowed to stand for 10 minutes, and soil pH was determined with silver chloride and a combination electrode.

Total Carbon and Total Nitrogen

For total soil carbon and total nitrogen, soil samples were air-dried, ground to pass through 2.00 mm sieve and sent to a commercial laboratory and the measurements were determined using a dry combustion analyzer. Samples were analyzed for total carbon and total nitrogen using an automated dry combustion C/N analyzer (Model NA 1500 NC; Carlo Erba, Milan, Italy) (Adeli et al., 2007) and oxidized above 950 ^{o}C under purified oxygen (Nelson and Sommers, 1996). For this method, samples are weighed in a crucible and introduced to a resistance furnace. Soil sample combustion conducted with O_2 above 950 ^{o}C and converted to CO2 and N_2, which was detected by a N2 analyzer and CO_2 detector.

Extractable Macro and Micro-nutrients

The soil samples were air-dried, ground to pass through 2.00 mm sieve and the extractable macro- and micro-nutrients like P, K, Mg, Mn, Ca, S, and Zn were measured by

Mehlich-3 extraction method in a commercial laboratory. The soil nutrients are extracted with the use of inductively coupled plasma optical emission spectrometry (ICP-OES) along with the Mehlich -3 extractant.

Organic Matter

Soil organic matter is considered as the one of the critical soil health indicators and is measured by calculating the sample weight loss on ignition at 360^{o} C. In general, organic matter can be determined from Total Carbon (TC) content in the soil by multiplying the TC by 1.72

Cation Exchange Capacity

The cation exchange capacity of a soil is the total negative charge of a soil, or it can be determined by the total number of cations that a soil can hold. CEC was measured using an extraction method where the difference between cation (Ca/Mg/ K) added and amount retained in the solution is calculated to determine the CEC. CEC, in general is measured in milliequivalents per 100 grams of soil (meq/100g).

Soil Health Score

For soil health assessment, we used Soil Management Assessment Framework (SMAF) method, where the Standard Scoring Functions (SSF) based curves were developed for normalizing different health indicators (physical, hydraulic, and chemical) of soil. The SSF curves developed by Karlen and Stott, (1994) characterized the health scores into four curves such as “more is better”, “less is better”, “optimum” and “undesirable range”. Then based on the obtained curves, the soil indicators were converted into a range of unitless, 0 to 1 scores which can be calculated mathematically to make desired comparisons. For this study, Principal Component Analysis (PCA) is the type of mathematical tool that was used to obtain the health indicator weights to establish SSF curves. The physical health indicators considered to calculate the health score are Bulk density and plant available water content and the chemical health indicators considered to determine the soil health score are soil pH, total carbon, total nitrogen, cation exchange capacity, available phosphorus (P) and extractable potassium content (K). The data values were normalized using the following equation developed by Imam, (1994); Wymore, (1993).

$$Y(a, b, c, S, x) = \frac{1}{1 + \left(\frac{b - a}{x - a}\right)^{2x\,S\,(b + x - 2a)}}, x \geq a \text{ and } 0, x < a \quad (2.5)$$

To determine the SSF curve shape, parameters like a, b, c, and S were determined, where c= upper threshold parameter, b = baseline parameter, a = lower threshold parameter, y = 0.5, x is the soil indicator value, S= slope value at baseline. Once the data was normalized, soil health score was calculated with the mathematical tool PCA using the following equation:

$$\text{Soil Health} = \sum \text{wi x yi} \quad (2.6)$$

where, y = normalized data of soil health indicator, w= weight of each soil health indicator (Chang et al., 2022)

Statistical Analysis

To determine the effects of treatments on variables, a general linear model ANOVA was used for data analysis**.** All the components were subjected to ANOVA with R programming (version 4.2.2) using the “agricolae” packages. In this study, the cover crop treatment differences were determined by the Fisher’s least significant difference test at the 0.05 probability level. The cover crop was considered as a whole plot factor and the fertilizer source was considered as a split factor.

Results and Discussion

In general, analyses of the soil's physical and chemical properties indicated that changes have resulted from adopting sustainable management practices such as cover cropping and poultry litter application. To understand the influence of different cover crop species and poultry litter on various soil health indicators, the following components are an in-depth discussion.

Soil bulk density

As summarized in Table 2.3 the soil bulk density was significantly reduced with the application of poultry litter by 5% as compared to no fertilizer treatment at each depth 0-5 and 5-10 cm. These results are similar to Byrne et al., (2004), who reported that poultry manure reduced the bulk density by 3% with the increase in the application rate in the surface 10 cm soil. Mandal et al., (2013) observed that poultry litter application decreases the soil bulk density by 42% in the topsoil. The cover crop integration showed no effect on bulk density in the topsoil (0-5 cm) but cereal rye cover crop significantly reduced the bulk density by 5.14% at the depth 5-10 cm as displayed in Table 2.2 & Figure 2.3. Poultry litter has the potential to reduce soil compaction by making the soil fluffier and healthy. A study conducted by (Adebayo et al., 2017) reported that reduced soil bulk density is a result of organic residue addition which improved the soil structure and water infiltration rate. Furthermore, Mau et al., (2020) recently stated that the addition of poultry manure was beneficial as an amendment which resulted in reduced bulk density.

Saturated hydraulic conductivity (Ksat)

The integration of cover crops and poultry litter showed little effect on the Ksat. Although not significantly different, the cereal rye and mustard (mix) followed by vetch resulted in higher values of Ksat at the depth 0-5 cm (Table 2.2). Like that, winter wheat and cereal rye showed higher values of Ksat but there was no significant difference among the cover crop species. Applying poultry litter for five years has showed an increasing trend in Ksat values as compared to no fertilizer treatment (0.03 vs 0.02 $cm.min^{-1}$) as well as fertilizer treatment (0.03 vs 0.02 $cm.min^{-1}$) at the depth 0-5 cm (Table 2.3). Our results show that, at the depth of 5-10 cm, PL increased the Ksat of soil by 300% (0.02 vs 0.005) as compared to no fertilizer treatment (control). Similarly, Khalid et al., (2014) reported that poultry manure has positive effects on the water infiltration rate in the soil. The results agree with several studies by Wuddivira et al., (2009); Bhattacharyya et al., (2007) who stated that soils amended with animal manures resulted in higher Ksat as compared to other fertilizer treatments. The comparatively low Ksat values of inorganic fertilizer and no fertilizer plots may be due to the high bulk density and these results agree with the study conducted by Feng et al., (2019b).

Soil water retention

Soil water retention parameters include soil water holding capacity (FC), permanent wilting point (PWP) and the plant available water content (PAW). Table 2.2 displays that as compared to native vegetation (control), mustard and cereal rye (mix) could significantly increase the soil water holding capacity by 4.17% respectively at 5-10 cm depth. There was a significant interaction between the cover crop and fertilizer treatment on soil water holding capacity and wilting point at each of the depths 0-5 and 5-10 cm Table 2.11). Cover crop showed no significant effect on the PAW, but the plots integrated with winter wheat cover crop has relatively more available water content for crop use at 0-5 cm depth as compared to other cover crop species and control (Figure 2.5). Poultry litter application, on the other hand, could significantly increase the soil water holding capacity by providing a soil cover which has led to conservation of soil moisture. At the soil depth 5-10 cm, poultry litter resulted in higher soil water holding capacity as compared to no fertilizer treatment (Figure 2.4). The addition of poultry litter to soil surface has evidently increased the percentage of water content availability for crop use by 1.2% in the topsoil and by 27% in the subsoil as compared to no fertilizer treatment. A Study by Warren and Fonteno, (1993) revealed that there was a 100 to 116% increase in the PAW in the soils amended with the poultry manure. Similarly, Meek et al.,(1992); Powell, (1986) studies explicitly tell us that available water capacity is 2, 19 and 27% greater than the control treatment respectively. However, the effects of poultry litter on soil water retention parameters can greatly vary with soil texture, bulk density (Reddy et al., 2008; Tyson and Cabrera, 1993).There was no noticeable significant interaction between the cover crop and fertilizer source on PAW.

Total carbon and total nitrogen

Cover crops had no effect on total carbon and total nitrogen at any depth as summarized in (Table 2.3). However, the cover crops such as cereal rye mixed with mustard and cereal rye has increased the total carbon content in the soil by 14.5% and 3.4% respectively. It is observed from our results that the addition of poultry litter has increased the total carbon content and total nitrogen content in the topsoil (0-5 cm). The poultry litter application sequestered 8.1% more carbon than the inorganic fertilizer and 24% more than the no fertilizer treatment (Table 2.4). The soils amended with manure retained 16% more carbon in the soil depth 0-10 cm as compared to no fertilizer treatment. Our findings were similar to results of Gao and Chang, (1996a) who reported that 18 years of manure application could significantly increase carbon content in the surface soil. The soils integrated with poultry litter has resulted in greater biomass production as compared to no fertilizer treatment (Table 2.9) which can be the reason for the accumulation of carbon content in the soil. The cover crop biomass generated each year from different cover crop species are summarized in Table 2.10. Manure application is considered as a supplemental source of nutrients and is known to increase the organic nitrogen content in soil by 16% (Koelsch, 2018). Our results tell us that N content was significantly increased in the 0-5 cm depth, but no changes were observed below 5 cm. Similar results were established in the studies conducted by Torbert et al., (1999, 1997), who reported that manure application did not show any significant effect below 5 cm depth. Eghball, (2002) reported that 55% of the nitrogen content in poultry litter becomes available to crops in the year of application and 45% of the nitrogen content is available in the following years.

Soil pH

In general, soil pH can be altered with the use of cover crops as it adds nitrogen to soil and addition of manure can effectively change the pH of soil that is correlated with the organic matter of soil. Our findings show that, with an exception to winter wheat cover crop at the 5-10 cm depth, no other over crop showed any significant effect on soil pH, but vetch followed by cereal rye and mustard (mix) showed reduced soil pH as compared to other cover crop treatment at both depths (Table 2.3). Poultry litter on the other hand has significantly affected the soil pH in the topsoil (0-5 cm) (Table 2.4).

Cation exchange capacity (CEC)

Cover crop did not show any positive influence on the cation exchange capacity at both depths and at the combined depth as displayed in Table 2.3. Although not significant, the vetch cover crop has increased the CEC by 15.9% and cereal rye mixed with mustard has increased the CEC by 3.07% as compared to native vegetation (control). The application of poultry litter has tremendously increased the CEC of soil by 11% as compared to no fertilizer treatment at the depth 0-10 cm (Table 2.4). Similar to this, Gao and Chang, (1996b) reported that 18 years of litter application increased the soil CEC by 21% in the depths 0-5 and 5-10 cm. Improved cation exchange capacity indicates that the soil has lower amount of cations and less prone to nutrient leaching leading to greater soil fertility. There was no noticeable significant interaction between the cover crop and fertilizer source at any depth.

Extractable macro and micro-nutrients

Cover crop did not show any significant effect on phosphorus, potassium, magnesium, calcium, sulfur, sodium, and zinc at any depth (Table 2.5) & (Table 2.6). Soils amended with poultry litter application for continuous five years showed higher concentrations of P, K, Mg, Ca, and S creating a reservoir of nutrients for future crop production. These results agree with studies reported by Mugwira, (1979); Sainju et al., (2008); Wood et al., (1996).When averaged across all fertilizer treatments, significantly higher concentrations ($p<0.0001$) of P, K, Mg, S and Ca were observed in the surface depths 0-5 and 5-10 cm of the plots integrated with poultry litter as compared to fertilizer treatments (Table 2.7) & (Table 2.8). At the depth 0-10cm, the litter amended soils has resulted in an increase of Ca, Mg, K, Na, S, Zn and P by 4.4%, 27.06%, 47%, 53.05%, 250%, 262% and 538.6% respectively. With the exception to Na levels, no other nutrients showed a significant interaction between cover crop and fertilizer source at the depth 0-10 cm.

Soil Health Score

Soil health assessment is a way to understand the effectiveness of management practices being followed in agricultural systems. The Standard Scoring Functions (SSF) based soil health scores associated with SMAF (Soil Management Assessment Framework) combined with Principal Component Analysis (PCA) are developed by normalizing the data and weight calculation from SSF parameters and PCA weights respectively as summarized in Table 2.14. The mathematical tool PCA was used for weight reductions and the SSF parameters have been determined using the selected critical (upper, lower, and baseline threshold) values to normalize the data. Similar approaches have been followed by Gelaw et al., (2015); Bhaduri and Purakayastha, (2014); Masto et al., (2007) to obtain the soil health scores. Chang et al., (2022) has reported that SSF is an effective soil health assessment method to differentiate the treatments differences on soil health scores. The impact of poultry litter on soil health indicators is the focus in this study and the assessment method we have used in our study has shown that PL use can improve soil health as compared to other fertilizer treatments (Table 2.15). The principal components of the selected indicators accounted for 61.3%, 14.3%, 8.64% with a cumulative variance of 84.24%.

Conclusion

A field experiment was conducted to evaluate the effects of five cover crop species and three fertilizer sources on different soil physical, hydraulic and soil chemical health indicators at two soil depths 0-5 and 5-10 cm in a no-tillage dryland system in Pontotoc, MS. The hypothesis of this research stated that use of Cover Crops and Poultry Litter will improve soil physical health and soil chemical health. Our findings show that cover crop integration may not affect all the soil health indicators over a period. However, the poultry litter and a few cover crop species affected some of the selected soil health indicators that can potentially improve soil health. The cover crop treatments resulted in an increasing trend of all the measured soil health indicators as compared to native vegetation (control). The soils amended with PL reduced bulk density and increased the plant available water content by 5% and 27% respectively which suggests that soil water storage is higher with the application of manure. In addition to this, PL sequestrated 8% more carbon content than the fertilizer treatment and 16 % more than the no fertilizer treatment in 0-10 cm depth which indicates improved the organic matter in the soil. PL application for five years has significantly increased the potassium, magnesium, calcium, sodium, sulfur, zinc, and phosphorus levels in the soil by 47%, 27.06%, 4.4%, 53.05%, 250%, 262%, and 538.6% respectively as compared to no fertilizer treatment, creating a nutrient reservoir for the following crop. Whereas there was not much difference between the soil physical characteristics between soils amended with PL and inorganic fertilizer. CC like cereal rye, cereal rye, and mustard (mix) increased the total carbon content in the soil by 3.4% and 14.5% respectively and cereal rye decreased the bulk density by 5.14% as compared to native vegetation (control). Similarly, as compared to control, winter wheat increased the Soil Water Holding Capacity (SWC) by 3.15% in the topsoil (0-5 cm) and cereal rye and mustard (mix) has potentially increased the SWC by 4.17% in the subsoil (5-10 cm) suggesting that cover crop integration has improved soil water content in 0-10 cm depth. As compared to control, CEC was found to be increased by 3.07% and 15.09% by cereal rye and mustard (mix) and vetch cover crops respectively. Both soil physical and chemical health scores were increased with PL as compared to other fertilizer treatments. Results suggest that cover crop integration and poultry litter application can be alternative management practices that can help rejuvenate soil health after a certain period.

Tables

Table 2.2 Main effects of cover crops such as Native Vegetation (NV), Cereal Rye (CR), Winter Wheat (WH), Vetch (VE), Cereal Rye and Mustard (mix) (CRm) on mean soil bulk density, soil water holding capacity, permanent wilting point, available water content and saturated hydraulic conductivity (Ksat) at two soil depths 0-5 and 5-10 cm.

Cover crop Treatment	**Bulk density † g cm^{-3}**	**Soil water holding capacity %**	**Permanent wilting point %**	**Available water content %**	**Ksat cm.min^{-1}**
0-5 cm depth					
NV	1.14 (0.01)	26.30 (0.35) §	16.12 (0.35)	10.16 (0.37)	0.0157 (0.005)
CR	1.18 (0.01)	26.68 (0.36)	16.87 (0.35)	9.88 (0.34)	0.0018 (0.011)
WH	1.18 (0.01)	27.13 (0.65)	16.81(0.35)	10.32 (0.17)	0.0059 (0.028)
VE	1.19 (0.01)	26.14 (0.72)	16.87 (0.35)	9.87 (0.21)	0.026 (0.008)
CRm	1.15 (0.01)	26.01 (0.46)	16.49 (0.35)	9.52 (0.38)	0.02 (0.008)
5-10cm depth					
NV	1.36 (0.01) a	27.32 (0.45) ab	19.70 (0.35) ab	7.62 (0.73)	0.0156 (0.008)
CR	1.29 (0.01) b	26.94 (0.40) abc	19.93 (0.35) ab	7.00 (0.79)	0.017 (0.009)
WH	1.39 (0.01) a	24.61 (1.59) bc	16.84 (0.35) b	7.76 (0.44)	0.018 (0.015)
VE	1.39 (0.01) a	24.06 (1.90) c	17.24 (0.35) b	7.03 (0.51)	0.005 (0.001)
CRm	1.41 (0.01) a	28.46 (0.39) a	21.19 (0.35) a	7.26 (0.45)	0.0017 (0.0007)

†Variables in column with no letters are not significant at the 0.05 level using Fisher's Protected LSD.

§ Standard error of means in parenthesis.

Table 2.3 Main effects of fertilizer treatments on mean soil bulk density, soil water holding capacity, permanent wilting point, available water content and saturated hydraulic conductivity (Ksat) at two soil depths 0-5 and 5-10 cm.

Fertilizer Treatment	Bulk density † $g\ cm^{-3}$	Soil water holding capacity %	Permanent wilting point %	Available water content %	Ksat $cm.min^{-1}$
0-5 cm depth					
None	1.20 (0.01) a	25.97 (0.21) §	16.10 (0.24) b	9.90 (0.11)	0.027 (0.008)
Fertilizer	1.17 (0.01) a	26.47 (0.49)	16.53 (0.37) ab	9.93 (0.26)	0.021 (0.005)
Poultry Litter	1.14 (0.01) b	27.28 (0.40)	17.26 (0.34) a	10.02 (0.31)	0.034 (0.018)
5-10cm depth					
None	1.40 (0.01) a	23.95 (1.41) b	17.66 (1.36)	6.29 (0.37) b	0.0053 (0.002)
Fertilizer	1.38 (0.01) a	27.54 (0.40) a	19.87 (0.36)	7.67 (0.39) ab	0.0100 (0.005)
Poultry Litter	1.33 (0.02) ab	27.34 (0.36) a	19.42 (0.40)	8.05 (0.48) a	0.0200 (0.010)

†Variables in column with no letters are not significant at the 0.05 level using Fisher's Protected LSD.
§ Standard error of means in parenthesis.

Table 2.3 Main effects of different cover crops such as Native Vegetation (NV), Cereal Rye (CR), Winter Wheat (WH), Vetch (VE), and Cereal Rye and Mustard (Mix) on total carbon, total nitrogen, soil pH and cation exchange capacity at 0-5, 5-10 and at combined depth (0-10 cm).

Cover crop Treatment	**Total carbon †** **%**	**Total nitrogen** **%**	**Soil pH**	**Cation exchange capacity** **meq/100g**
0-5 cm depth				
NV	1.46 (0.07) ∬	0.16 (0.01)	5.70 (0.11)	8.46 (0.33)
CR	1.54 (0.06)	0.19 (0.01)	5.62 (0.11)	8.53 (0.20)
WH	1.50 (0.08)	0.18 (0.01)	5.66 (0.06)	8.54 (0.38)
VE	1.56 (0.08)	0.18 (0.01)	5.38 (0.10)	9.62 (0.67)
CRm	1.75 (0.10)	2.00 (0.01)	5.46 (0.08)	8.72 (0.48)
5-10 cm depth				
NV	0.88 (0.03)	0.09 (0.008)	5.99 (0.13) b	7.96 (0.52)
CR	0.88 (0.02)	0.10 (0.006)	6.02 (0.07) b	8.67 (0.40)
WH	0.85 (0.02)	0.10 (0.010)	6.18 (0.08) a	7.77 (0.30)
VE	0.91 (0.09)	0.09 (0.010)	5.69 (0.11) b	9.42 (0.71)
CRm	0.94 (0.02)	0.10 (0.010)	5.53 (0.08) c	9.52 (0.48)
0-10 cm depth				
NV	1.17 (0.08)	0.13 (0.01)	5.84 (0.09) a	8.21 (0.31) b
CR	1.21 (0.09)	0.14 (0.01)	5.82 (0.08) a	8.60 (0.22) b
WH	1.17 (0.09)	0.13 (0.01)	5.91 (0.08) a	8.15 (0.26) b
VE	1.24 (0.09)	0.14 (0.01)	5.53 (0.08) b	9.52 (0.48) a
CRm	1.34 (0.11)	0.15 (0.01)	5.68 (0.08) b	8.62 (0.29) b

†Variables in column with no letters are not significant at the 0.05 level using Fisher's Protected LSD.

∬ Standard error of means in parenthesis.

Table 2.4 Main effects of different fertilizer treatments on mean total carbon, total nitrogen, soil pH and cation exchange capacity at two soil depths 0-5, 5-10 cm and at combined depth 0-10 cm.

Fertilizer Treatment	Total carbon † %	Total nitrogen %	Soil pH	Cation exchange capacity meq/100g
0-5 cm depth				
None	1.39 (0.05) b	0.16 (0.009) b	5.68 (0.07) a	7.95 (0.28) b
Fertilizer	1.59 (0.04) ab	0.19 (0.009) ab	5.35 (0.06) ab	9.05 (0.26) a
Poultry Litter	1.72 (0.07) a	0.20 (0.009) a	5.64 (0.07) a	9.36 (0.39) a
5-10 cm depth				
None	0.86 (0.02) ∮	0.09 (0.008)	6.02 (0.08)	8.09 (0.39)
Fertilizer	0.91 (0.01)	0.10 (0.008)	5.85 (0.07)	8.69 (0.32)
Poultry Litter	0.92 (0.02)	0.10 (0.007)	6.00 (0.09)	8.63 (0.43)
0-10 cm depth				
None	1.12 (0.05) b	0.12 (0.009) ab	5.85 (0.06) a	8.02 (0.24) b
Fertilizer	1.25 (0.06) a	0.14 (0.010) a	5.60 (0.06) ab	8.87 (0.20) ab
Poultry Litter	1.31 (0.08) a	0.15 (0.011) a	5.83 (0.06) a	8.98 (0.29) a

†Variables in column with no letters are not significant at the 0.05 level using Fisher’s Protected LSD.
∮ Standard error of means in parenthesis.

Table 2.5 Main effects of cover crop such as Native Vegetation (NV), Cereal Rye (CR), Winter Wheat (WH), Vetch (VE), Cereal Rye and Mustard (mix) (CRm) on mean Phosphorus (P), Potassium (K), Magnesium (Mg), and Calcium (Ca) in mg kg-1 at two soil depths 0-5, 5-10 cm and at combined depth 0-10 cm.

Cover crop Treatment	**P †**	**K**	**Mg**	**Ca**
0-5 cm depth				
NV	64.67 (17.84) §	193.56 (18.45)	120.11 (8.77)	1005.78 (47.55)
CR	37.89 (8.55)	205.33 (18.77)	116.00 (9.60)	989.56 (41.54)
WH	41.56 (8.55)	173.33 (18.90)	115.22 (8.73)	1025.11 (57.35)
VE	50.44 (17.84)	198.56 (17.84)	120.11 (17.84)	1007.89 (17.84)
CRm	53.67 (17.84)	188.56 (17.84)	114.56 (17.84)	956.78 (17.84)
5-10 cm depth				
NV	9.78 (2.47)	125.56 (13.56)	103.44 (8.58)	1071.33 (63.12)
CR	6.67 (0.94)	143.89 (13.95)	108.33 (7.56)	1198.33 (66.51)
WH	7.22 (1.07)	117.89 (11.56)	98.78 (5.24)	1121.67 (64.97)
VE	7.67 (17.84)	129.67 (17.84)	109.67 (17.84)	1197.22 (17.84)
CRm	7.77 (17.84)	130.00 (17.84)	106.66 (17.84)	1147.77 (17.84)
0-10 cm depth				
NV	37.22 (10.98)	159.56 (13.83)	111.78 (6.29)	1038.56 (39.15)
CR	22.28 (5.64)	174.61 (13.58)	112.17 (6.00)	1093.94 (45.70)
WH	24.38 (5.90)	145.61 (12.68)	107.00 (5.33)	1073.38 (43.64)
VE	29.06 (18.00)	164.11 (13.23)	114.89 (6.79)	1102.56 (56.40)
CRm	30.72 (8.19)	159.27 (14.02)	110.61 (6.16)	1052.27 (39.26)

†Variables in column with no letters are not significant at the 0.05 level using Fisher's Protected LSD.
§ Standard error of means in parenthesis.

Table 2.6 Main effects of cover crops such as Native Vegetation (NV), Cereal Rye (CR), Winter Wheat (WH), Vetch (VE), Cereal Rye and Mustard (mix) (CRm) on mean Sulfur (S), Sodium (Na), and Zinc (Zn) in mg kg-1 at two soil depths 0-5, 5-10 cm and at combined depth 0-10 cm.

Cover crop Treatment	**S †**	**Na**	**Zn**
0-5 cm depth			
NV	19.11 (1.84) b	17.33 (1.06) §	6.66 (1.68)
CR	20.22 (2.28) ab	18.56 (2.05)	5.46 (1.43)
WH	18.67 (1.52) b	18.00 (1.06)	4.96 (1.13)
VE	25.67 (4.03) a	19.56 (2.70)	5.69 (1.29)
CRm	20.44 (2.15) ab	16.67 (0.95)	5.57 (1.19)
5-10 cm depth			
NV	17.11 (2.08)	20.67 (1.81)	2.09 (0.67)
CR	15.11 (2.09)	20.22 (2.29)	1.62 (0.27)
WH	14.00 (1.44)	19.11 (1.05)	1.27 (0.12)
VE	19.22 (2.26)	21.22 (2.39)	1.42 (0.12)
CRm	15.44 (1.45)	18.88 (0.75)	1.51 (0.18)
0-10 cm depth			
NV	18.11 (1.37)	19.00 (1.10)	4.37 (1.04)
CR	17.67 (1.63)	19.39 (1.51)	3.54 (0.85)
WH	16.33 (1.17)	18.55 (0.74)	3.11 (0.71)
VE	22.44 (2.38)	20.39 (1.77)	3.56 (0.81)
CRm	17.94 (1.39)	17.77 (0.65)	3.53 (0.77)

†Variables in column with no letters are not significant at the 0.05 level using Fisher's Protected LSD.
§ Standard error of means in parenthesis.

Table 2.7 Main effects of different fertilizer treatments on mean Phosphorus (P), Potassium (K), Magnesium (Mg), and Calcium (Ca) in mg kg-1 at two soil depths 0-5, 5-10 cm and at combined depth 0-10 cm.

Fertilizer Treatment	P †	K	Mg	Ca
0-5 cm depth				
None	9.40 (0.41) b	158.20 (8.41) b	106.67 (3.09) b	962.13 (42.93) b
Fertilizer	66.13 (4.03) ab	172.87 (9.09) b	101.47 (4.74) b	980.20 (29.95) b
Poultry Litter	73.79 (9.38) a	244.14 (14.28) a	142.64 (7.36) a	1048.50 (35.48) ab
5-10 cm depth				
None	7.87 (0.30) c	116.53 (6.48) b	100.67 (4.94) b	1128.20 (66.01) ᛩ
Fertilizer	15.60 (0.89) b	110.20 (5.60) b	95.47 (4.59) b	1179.80 (45.82)
Poultry Litter	23.47 (2.85) a	161.47 (9.74) a	120.00 (5.58) a	1133.80 (43.52)
0-10 cm depth				
None	13.33 (1.10) b	137.37 (6.49) b	103.67 (2.92) b	1045.17 (41.65)
Fertilizer	28.50 (11.54) b	141.53 (7.83) b	98.47 (3.29) b	1080.00 (32.66)
Poultry Litter	42.56 (14.76) a	203.00 (11.47) a	131.73 (5.03) a	1091.27 (28.69)

† Means followed by different letters in column are significantly different at the 0.05 level and variables with no letters are not significantly different

ᛩ Standard error of means in parenthesis.

Table 2.8 Main effects of different fertilizer treatments on mean Sulfur (S), Sodium (Na), and Zinc (Zn) in mg kg-1 at two soil depths 0-5 and 5-10 cm and at combined depth 0-10 cm.

Fertilizer Treatment	S †	Na	Zn
0-5 cm depth			
None	13.67 (0.36) b	14.93 (0.15) b	1.65 (0.07) b
Fertilizer	25.87 (1.94) a	16.53 (0.61) b	7.23 (0.91) ab
Poultry Litter	23.07 (1.60) a	22.57 (1.59) a	8.14 (0.80) a
5-10 cm depth			
None	10.53 (0.66) b	16.47 (0.35) b	1.09 (0.06)
Fertilizer	18.47 (1.30) a	18.13 (0.48) b	1.92 (0.42)
Poultry Litter	19.53 (1 .12) a	25.47 (1.42) a	1.80 (0.10)
0-10 cm depth			
None	12.10 (0.47) b ᶊ	15.70 (0.23) b	1.37 (0.07) b
Fertilizer	22.17 (1.33) a	17.33 (0.41) b	4.54 (0.70) a
Poultry Litter	42.47 (2.02) a	24.03 (1.08) a	4.96 (0.70) a

† Means followed by different letters in column are significantly different at the 0.05 level and variables with no letters are not significantly different.
ᶊ Standard error of means in parenthesis.

Table 2.9 Main effects of fertilizer source on mean cover crop biomass from year 2019 till 2022 with p-values.

	Cover crop biomass (Kg/ha)			
Fertilizer source	2019 †	2020	2021	2022
None	1766.7 (339.52) ∮ b	999.0 (304.90) b	571.63 (346.86) c	1216.25 (485.05) b
Inorganic fertilizer	3081.7 (559.53) a	1919 (290.15) a	1717.13 (477.81) b	1676.25 (330.78) ab
Poultry Litter	3066.4 (628.15) a	2070 (312.45) a	2754.88 (680.00) a	1976.25 (375.33) a
P - value	<0.001	<0.001	<0.001	0.034

† Means followed by same letters within a column are not significantly different at the 0.05 level and variables with no letters are not significantly different.
∮ Standard error of means in parenthesis.

Table 2.10 Main effects of cover crop treatments such as Cereal Rye (CR), cereal rye mixed with mustard (CRm), Vetch (VE), Winter Wheat (WH), and Native Vegetation (NV) on cover crop biomass with p-values.

	Cover crop biomass (Kg/ha)			
Cover crop	2019 †	2020	2021	2022
CR	3303.67 (543.52) ∮ a	1755.83 (469.82) a	835.5 (307.70) b	1456.67 (410.80) b
CRm	3673.17 (490.07) a	1882.50 (447.38) a	1878.83 (781.72) ab	1443.33 (287.78) b
NV	1276.17 (189.86) c	1435.00 (332.41) a	-	-
VE	1987.83 (357.77) bc	1320.83 (278.69) a	1145.17 (441.05) b	995 (127.00) b
WH	2950.50 (423.01) ab	1919.17 (302.61) a	2865.33 (637.58) ab	2596.67 (344.27) a
P - value	<0.001	0.197	<0.001	<0.001

† Means followed by different letters in column are significantly different at the 0.05 level and variables with no letters are not significantly different.
∮ Standard error of means in parenthesis.

Table 2.11 Probability values (p-values) and numerator degrees of freedom (df) associated with the sources of variance on soil physical health indicators such as Bulk Density (BD), Field Capacity (FC), Permanent Wilting Point (PWP), Available Water Content (AWC), and Saturated hydraulic conductivity (Ksat) as effected by the cover crop and fertilizer treatments.

Effect	**Df**	**BD** **g cm^{-3}**	**FC** **%**	**PWP** **%**	**AWC** **%**	**Ksat** **cm.min^{-1}**
0-5 cm depth						
Cover crop	4	0.17	0.42	0.67	0.07	0.50
Fertilizer	2	0.05	0.10	0.05	0.98	0.75
Cover crop*Fertilizer	8	0.73	0.07	0.02	0.50	0.85
5-10 cm depth						
Cover crop	4	0.0006	0.002	0.001	0.72	0.61
Fertilizer	2	0.01	0.004	0.13	0.0006	0.41
Cover crop*Fertilizer	8	0.35		0.02	0.31	0.57

Table 2.12 Probability values (p-values) and numerator of degrees of freedom (df) associated with the sources variance on soil chemical health indicators such as Total Carbon (TC), Total Nitrogen (TN), soil pH, and Cation Exchange Capacity (CEC) at soil depths 0-5 and 5-10 cm and at combined depth 0-10 cm.

Effect	**Df**	**TC**	**TN**	**Soil pH**	**CEC**
0-5 cm depth					
Cover crop	4	0.45	0.45	0.31	0.61
Fertilizer	2	0.001	0.006	0.002	<0.0001
Cover crop*Fertilizer	8	0.90	0.36	0.81	0.81
5-10 cm depth					
Cover crop	4	0.17	0.54	0.02	0.20
Fertilizer	2	0.15	0.49	0.26	0.007
Cover crop*Fertilizer	8	0.64	0.86	0.53	0.96
0-10 cm depth					
Cover crop	4	0.35	0.12	0.16	0.18
Fertilizer	2	0.002	0.003	0.01	0.01
Cover crop*Fertilizer	8	0.89	0.62	0.51	0.83

Table 2.13 Probability values (p-values) and numerator of degrees of freedom (df) associated with the sources variance on soil chemical health indicators such as Phosphorus (P), Potassium (K), Magnesium (Mg), Calcium (Ca), Sulfur (S), Sodium (Na), and Zinc (Zn) in mg.kg-1 at soil depths 0-5 and 5-10 cm and combined depth 0-10 cm.

Effect	**Df**	**P**	**K**	**Mg**	**Ca**	**S**	**Na**	**Zn**
0-5 cm depth								
Cover crop	4	0.11	0.34	0.77	0.81	0.01	0.35	0.62
Fertilizer	2	<0.0001	<0.0001	<0.0001	0.03	<0.0001	<0.0001	<0.0001
Cover crop*Fertilizer	8	0.16	0.87	0.55	0.61	0.77	0.31	0.20
5-10 cm depth								
Cover crop	4	0.56	0.40	0.46	0.38	0.04	0.23	0.64
Fertilizer	2	<0.0001	0.001	0.001	0.54	<0.0001	<0.0001	0.07
Cover crop*Fertilizer	8	0.60	0.91	0.86	0.94	0.31	0.06	0.68
0-10 cm depth								
Cover crop	4	0.13	0.20	0.51	0.78	0.002	0.22	0.37
Fertilizer	2	<0.0001	<0.0001	<0.0001	0.73	<0.0001	<0.0001	<0.0001
Cover crop*Fertilizer	8	0.23	0.72	0.43	0.89	0.70	0.40	0.59

Table 2.14 Normalized soil physical and chemical health indicators data by the method SSF (Standard Scoring Functions).

	Physical health indicators		Chemical health indicators					
Treatments	**BD**	**AWC**	**TC**	**TN**	**pH**	**CEC**	**P**	**K**
0-5 cm depth								
No fertilizer	0.87	0.040	0.72	0.820	0.56	0.24	0.007	0.21
Inorganic fertilizer	0.89	0.051	0.83	0.909	0.35	0.34	0.32	0.25
Poultry Litter	0.93	0.053	0.86	0.934	0.59	0.37	0.38	0.52
5-10 cm depth								
No fertilizer	0.49	0.01	0.29	0.32	0.71	0.26	0.005	0.46
Inorganic fertilizer	0.53	0.02	0.33	0.41	0.75	0.31	0.01	0.41
Poultry Litter	0.63	0.03	0.34	0.37	0.75	0.31	0.04	0.74

Note: BD = Bulk Density, AWC = Available water content, TC = Total Carbon, TN = Total Nitrogen, CEC = Cation Exchange Capacity, P = Phosphorus, K = Potassium

Table 2.15 Soil physical, chemical, and overall health scores as determined from SMAF (Soil Management Assessment Framework) based on SSF (Standard Scoring Function) values and PCA (Principal Component Analysis) weights of different fertilizer treatments and indication of soil health level at two soil depths 0-5 and 5-10 cm.

Treatments	Soil Physical Health Score	Soil Chemical Health Score	Overall Soil Health Score	Soil Health Level
0-5 cm depth				
No fertilizer	53.40	**35.65**	**44.52**	medium
Fertilizer	54.93	**45.23**	**50.08**	medium
Poultry Litter	57.39	**61.00**	**55.25**	medium
5-10 cm depth				
No fertilizer	35.65	**22.45**	**29.05**	low
Fertilizer	45.33	**24.52**	**34.92**	low
Poultry Litter	53.97	**38.35**	**46.12**	medium

Note: 0-20: very low; 20-40: low; 40-60: medium; 60-80: high; 80-100: very high

Figures

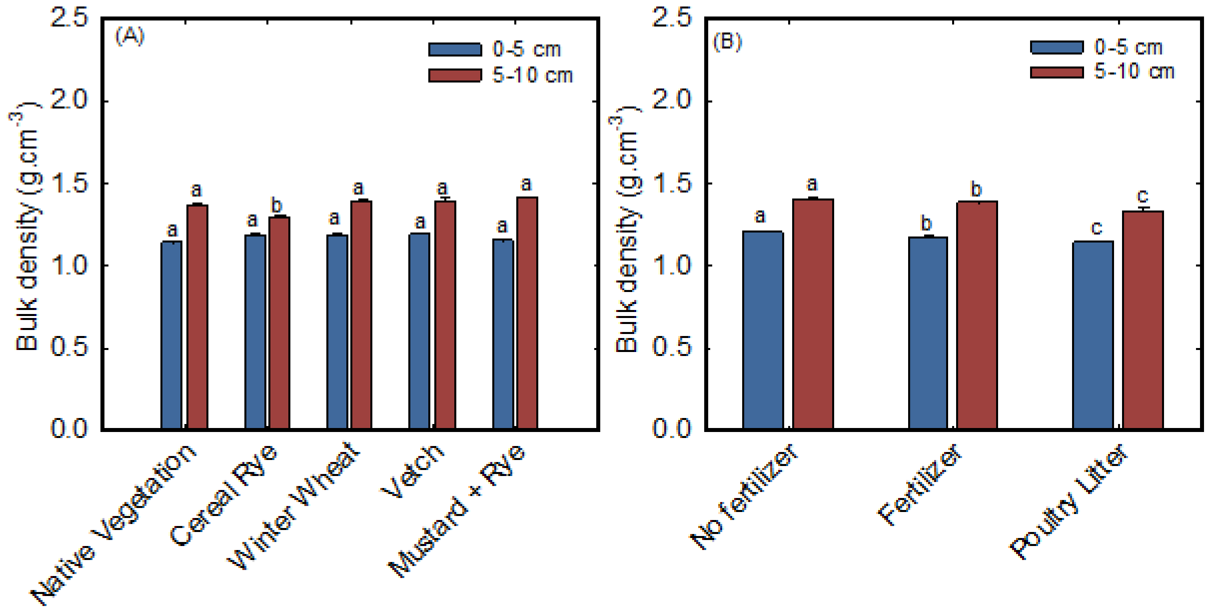

Figure 2.3 (A) – Effect of different cover crops on soil bulk density at two depths 0-5 and 5-10 cm. (B) – Effect of different fertilizer treatments on soil bulk density at two depths 0-5 and 5-10 cm.

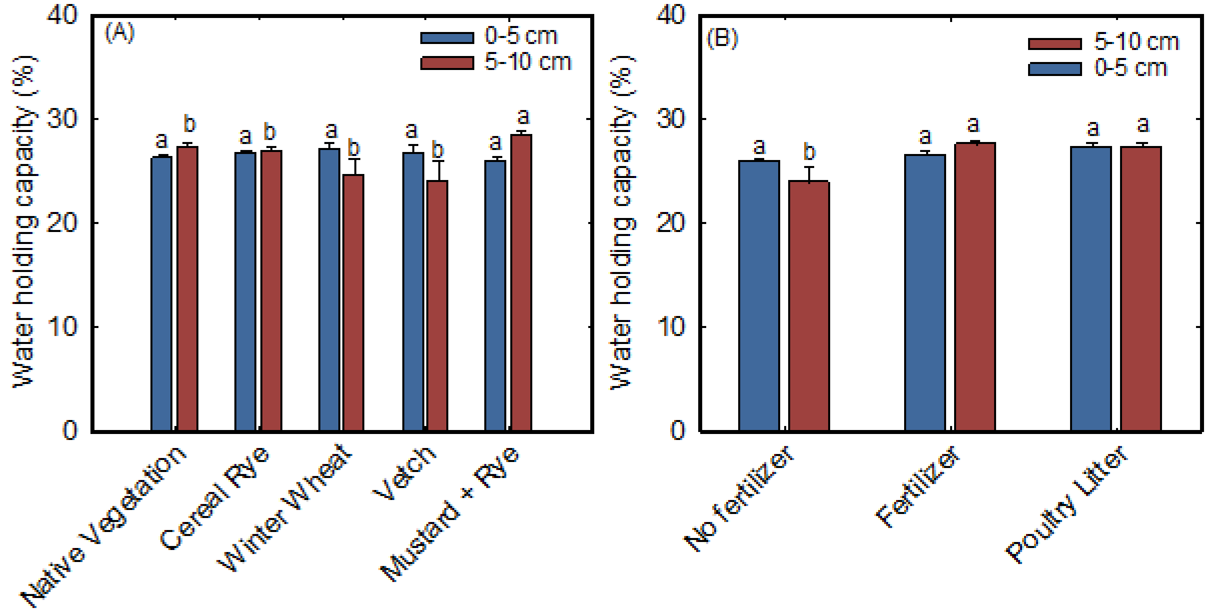

Figure 2.4 (A) - Effect of different cover crops on soil water holding capacity at depth 0-5 and 5-10 cm. (B) - Effect of different fertilizer treatments on soil water holding capacity at depth 0-5 and 5-10 cm

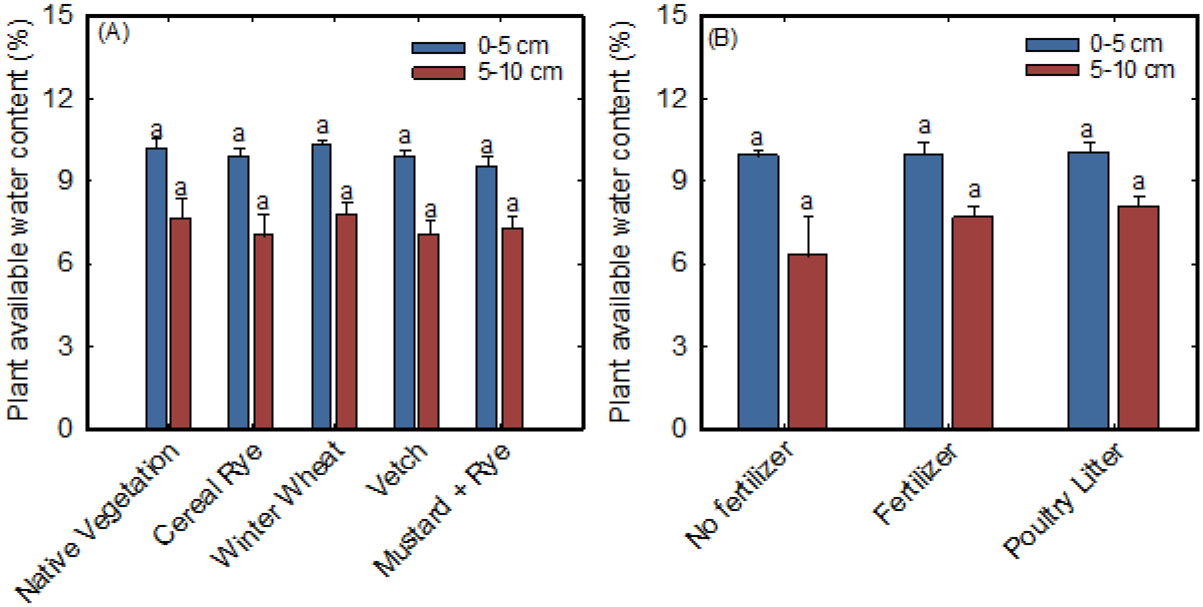

Figure 2.5 (A) - Effect of different cover crops on plant available water content at two depths 0-5 and 5-10 cm. (B) - Effect of different fertilizer treatments on plant available water content at two depths 0-5 and 5-10 cm

CHAPTER III

EFFECTS OF COVER CROP MANAGEMENT ON SOIL PHYSICAL AND SOIL CHEMICAL HEALTH

Abstract

Cover crop management is one of the best management practices that can help intensify crop productivity while benefiting the environment. However, there is a need to address the uncertainties of cover crop management and its impacts on soil physical and chemical health indicators. The objective of this study was to assess the effects of different cover crop species elbon rye, daikon radish, and Austrian winter filed peas on soil physical and chemical health in a Marietta silt loam soil under a corn and cotton rotation at two soil depths in R. R. Foil Plant Science Research Center, Mississippi State University. Cover crops were drill-seeded after the harvest of the primary cash crop in the fall and terminated before the planting of the following cash crop in 2019 through 2022. As compared to No Cover Crop treatment (NCC), cover crop treatments such as rye (DC2, FC2), peas (GC2) have potentially reduced the Bulk Density (BD) by 7.04%, 6.33% and 5.63% respectively in the topsoil (0-5 cm) and at the depth 5-10 cm, rye cover crop treatment (DC1) alone reduced the BD by 6.1%. Similarly, Available Water Content (PAW) in the topsoil was increased by 49%, 36% and 26% by mixed (EC1, CC1), and peas (BC1) cover crops respectively as compared to NCC (AC1). The saturated hydraulic conductivity (Ksat) and field capacity (FC) of soil were significantly affected by different cover crop treatments as compared to control in the subsoil. Further, soil chemical health indicators

such as total carbon, and organic matter were found to be higher in the plots integrated with rye (FC2, DC2), followed by the mixed cover crop treatments than the NCC. And soils with the mixture of cover crops had significantly increased potassium and manganese levels at the 0-10 cm depth. Cover crops showed no effect on field capacity, Ksat in the topsoil and PAW in the subsoil, other soil chemical health indicators such as total nitrogen, soil pH, Cation exchange capacity, phosphorus were not affected at the soil depth 0-10 cm. The quantification of soil health indicator data using the Soil Management Assessment Framework (SMAF) tells us that cover crop integration affected the soil physical and chemical health resulting in improved overall soil health score. These findings indicate the short-term cover crop management under a crop rotation can influence soil physical and soil chemical health indicators, more than 3 years are required to have cover crop taken significant effects.

Introduction

A cover crop is any non-cash crop grown in addition to the primary cash crop to cover the soil. Planting of cover crops has been one of the common conservation practices adapted to improve soil health by enhancing soil properties such as infiltration rate, aggregate stability, and mount of organic matter in the soil (Snapp et al., 2005). Soil health management can be achieved by following basic principles: 1) minimize disturbance 2) maximize biodiversity, 3) maximize soil cover 4) maximize living roots. Of these four basic principles for soil health management, three of them are met by the conservation practice “cover cropping” (USDA-NRCS, 2018). In United States, According to a series of farm and field level survey conducted by USDA economic research service, the use of cover crops has increased by 50 % between 2012 and 2017 (Wallander et al., 2021). Furthermore, in the southeastern states, more than 5% of the farmland (in hectares) adopted cover crops in the existing cropping systems (USDA-NASS, 2017). To address challenges like soil erosion, depleted soil health which are the consequences of continuous farming practices, the southeastern row crop producers have developed interest in cover cropping as one of the best conservation management practices to improve soil health and maximize biodiversity in the agroecosystems (St Aime et al., 2023).

In most states, after the harvest of primary cash crops, winter cover crops are planted and grown throughout the fall, winter and early spring and are terminated before another cash crop is planted. The adoption of winter cover crops has emerged as a sustainable management practice, as these crops would be grown in fall between the crop production cycles and provide many significant soil health benefits which can impact the crop production, climate change and resilience (DeVincentis et al., 2022). Several studies have demonstrated that the integration of cover crops in the agricultural systems can improve soil physical, chemical, and hydraulic properties (Adetunji et al., 2020; Saleem et al., 2020). In addition, cover crops have been found to enhance water infiltration rate, nutrient cycling, weed suppression and conserve soil moisture which can be utilized by the following cash crop in the production cycle (Sharma et al., 2018). A study by Norris and Congreves, (2018) revealed that across different climatic zones, the integration of cover crops may help rejuvenate the soil health although, the cover crop species selection and adoption of multi-species cover crops (mix) are dependent on various factors such tillage practices and crop rotation.

Several cover crop species have been utilized to achieve certain goals when incorporated into the cropping systems. Based on taxonomy, cover crops can be classified into leguminous broadleaves, non-leguminous broadleaves, and grasses. The cover crops planted in this study are Elbon rye (*Secale cereale L*.), Daikon Radish (*Raphanus sativus ssp. acanthiformis*), Austrian Winter Field Peas (*Lathyrus hirsutus*), and mixture of the three cover crop species. Elbon rye is a grass cover crop often grown for its ability to reduce soil erosion, add organic matter to soil, and scavenge excess nutrients (Vann et al., 2018; Clark, 2008). Daikon Radish is one of the Brassicas cover crops which can produce large taproots that can penetrate deep soil layers which can reduce soil compaction by holding the soil together. Along with this, brassicas can also facilitate water infiltration and aid in scavenging nutrients in the soil. Austrian Winter Field Peas is a legume cover crop commonly grown for fixing the atmospheric nitrogen, reduce run-off and suppress weed growth. Multi-species cover crops are known to provide many benefits to soil health, enhancing the soil properties (Florence and McGuire, 2020). Studies conducted by Bruce et al., (1991); Reeves, (1994) reported that with the incorporation of grass cover crops has reduced soil bulk density and increased the saturated hydraulic conductivity. In addition, these cover crops have been found to increase the soil water holding capacity which resulted in more plant available water content (Bilek, 2007; Blanco-Canqui and Ruis, 2020; Burke et al., 2021). However, there are studies which tells us that no effects were observed on the soil properties even after 15 years of cover crop integration in a cotton cropping system (Adhikari et al., 2017).

Across the world, producers are willing to integrate diversified cover crop species into cropping systems as a part of long-term sustainability (Clay et al., 2020). Therefore, there is a need to provide answers to many uncertainties on cover crop management and its impact on soil properties which can potentially improve soil health.

Materials and Methods

Study Site

A cover crop study is being conducted at the R. R. Foil Plant Science Research Center, Mississippi State University (33.4722° N, -88.7823° W). The study started in the year 2019 and continued till 2022. The soil series at the study site is Marietta silt loam (Fine-loamy, siliceous, active, thermic Fluvaquentic). The study was conducted under minimum tillage, rainfed conditions.

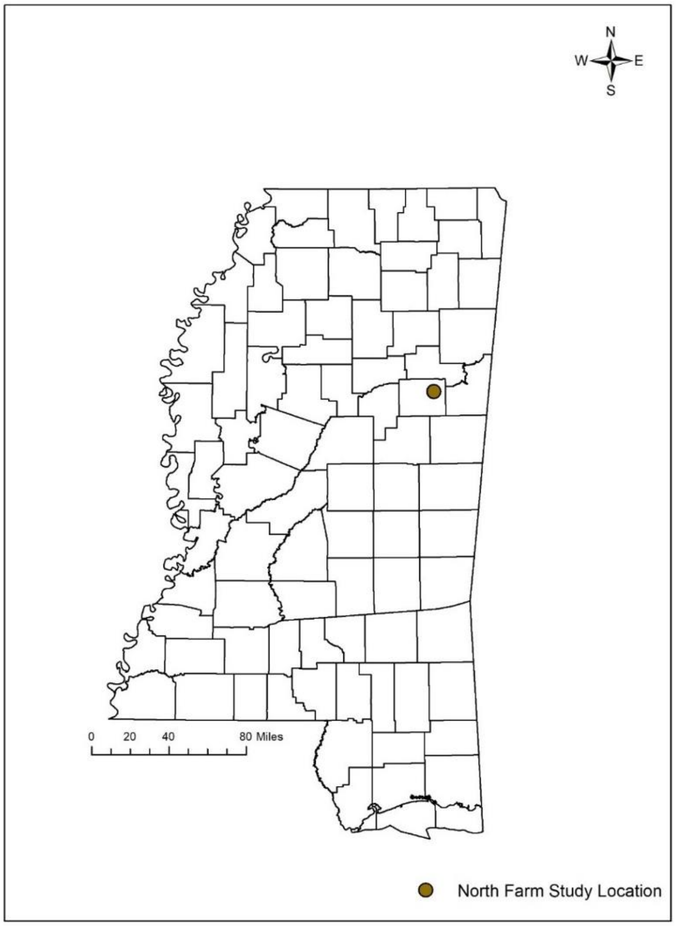

Figure 3.1 Study location (R.R. Foil Plant Science Research Center) on the map of Mississippi.

Experimental Design

The experimental design is a split-split plot structure with seven cover crop treatmentsTable 3.2)and four replications with a corn and cotton crop rotation. The cover crop treatments were planted in a randomized complete block in each replication. The whole plot (cover crop) is four rows wide by 182.9 meters (600 ft) long and the alley being 10.7 meters (35 ft).

The cover crop treatments at the R. R. Foil Plant Science Research Center included Elbon rye (*Secale cereale L*.), Daikon Radish (*Raphanus sativus ssp. acanthiformis*), Austrian Winter Field Peas (*Lathyrus hirsutus*), and mixture of the three cover crop species.

Field Methods

In the summer of 2019 soybeans were planted as a cash crop over the entire field to provide a common cash crop across the entire experiment before planting any cover crops. Cover crops were planted in the fall of 2019, 2020, and 2021. Cash crops were planted in south plots (C1) with cotton in 2020 and corn in 2021 and north plots (C2) with corn in 2020 and cotton in 2021(Table 3.3). The cash crops were planted across all 120 rows with 92 meters (300ft) in north end of field planted to corn and 92 meters (300 ft) in the south end of field planted to cotton in a rotation, where both cash crops were planted each year. All the cover crop treatments and the species composition each year are listed in the Table 3.2. Cover crops were drill-seeded at the rate of 67.25 kg ha $^{-1}$ Austrian winter field pea, and 14.27 kg ha $^{-1}$ daikon radish in the year 2020, 2021. Elbon rye was drill-seeded at the rate of 134.5 kg ha $^{-1}$ and 120 kg ha $^{-1}$ in the years 2020 and 2021 respectively. In the year 2022, winter field peas and elbon rye were drill-seeded at the rates of 67.25 kg ha $^{-1}$ and 134.5 kg ha $^{-1}$ respectively. A mixture of cover crops was applied at the rates of 33.63 kg ha $^{-1}$ winter field peas, 7.85 kg ha $^{-1}$ daikon radish and 67.25 kg ha $^{-1}$ elbon rye in the year 2022. Cover crop planting and termination dates information is listed in the CHAPTER 3.2Table 3.2. All the plots in the experiment field were fertilized with poultry litter at the rate of 2 tons per acre every fall.

Table 3.2 Cover crop treatments and species composition from year 2019 till 2021.

Treatment	Year 1 (2019)	Year 2 (2020)	Year 3 (2021)
AC1	No cover crop (NCC)	No cover crop (NCC)	No cover crop (NCC)
AC2	No cover crop (NCC)	No cover crop (NCC)	No cover crop (NCC)
BC1	Peas	Peas	Peas
BC2	Peas	Peas	Peas
CC1	Radish	Radish	Mixed (Peas + Radish + Rye)
CC2	Radish	Radish	Mixed (Peas + Radish + Rye)
DC1	Rye	Rye	Rye
DC2	Rye	Rye	Rye
EC1	Peas	Rye	Mixed (Peas + Radish + Rye)
EC2	Peas	Rye	Mixed (Peas + Radish + Rye)
FC1	Radish	Peas	Rye
FC2	Radish	Peas	Rye
GC1	Rye	Radish	Peas
GC2	Rye	Radish	Peas

Table 3.2 Planting and termination dates of cover crops from 2019 till 2022

	Cover Crop					
Treatment	**Planting date**			**Termination date**		
	2019	**2020**	**2021**	**2020**	**2021**	**2022**
AC1	Nov 11	Nov 16	Sep 29	April 4	March 10	April 15
AC2	Nov 11	Sep 9	Oct 10	March 18	April 19	March 14
BC1	Nov 11	Nov 16	Sep 29	April 4	March 10	April 15
BC2	Nov 11	Nov 16	Oct 10	April 4	April 19	March 14
CC1	Nov 11	Sep 9	Sep 29	March 18	March 10	April 15
CC2	Nov 11	Nov 16	Oct 10	April 4	April 19	March 14
DC1	Nov 11	Nov 16	Sep 29	April 4	March 10	April 15
DC2	Nov 11	Sep 9	Oct 10	March 18	April 19	March 14
EC1	Nov 11	Nov 16	Sep 29	April 4	March 10	April 15
EC2	Nov 11	Nov 16	Oct 10	April 4	April 19	March 14
FC1	Nov 11	Sep 9	Sep 29	March 18	March 10	April 15
FC2	Nov 11	Nov 16	Oct 10	April 4	April 19	March 14
GC1	Nov 11	Sep 9	Sep 29	March 18	March 10	April 15
GC2	Nov 11	Nov 16	Oct 10	April 4	April 19	March 14

Table 3.3 Cash crop rotation pattern from year 2019 to 2021

	Cash Crop		
Cover Crop Treatment	**2019**	**2020**	**2021**
AC1	Soybean	Cotton	Corn
AC2	Soybean	Corn	Cotton
BC1	Soybean	Cotton	Corn
BC2	Soybean	Corn	Cotton
CC1	Soybean	Cotton	Corn
CC2	Soybean	Corn	Cotton
DC1	Soybean	Cotton	Corn
DC2	Soybean	Corn	Cotton
EC1	Soybean	Cotton	Corn
EC2	Soybean	Corn	Cotton
FC1	Soybean	Cotton	Corn
FC2	Soybean	Corn	Cotton
GC1	Soybean	Cotton	Corn
GC2	Soybean	Corn	Cotton

Soil Sampling and Preparation

The soil samples were collected after the termination of cover crops in May 2022. We have done undisturbed core soil sampling at depths of 0-5 and 5-10 cm and collected disturbed soil samples at depths of 0-5 and 5-10 cm using soil auger. We have collected 340 undisturbed core samples and 112 disturbed soil samples in total at depths 0-5 and 5-10cm. Along with this, we have collected soil samples from 8 randomly selected native vegetation plots near the experiment site. For long-term storage, the soil was trimmed level with the upper and lower edges of the core ring and was wrapped around with a plastic cling wrap and kept in the refrigerator upon arrival in the laboratory.

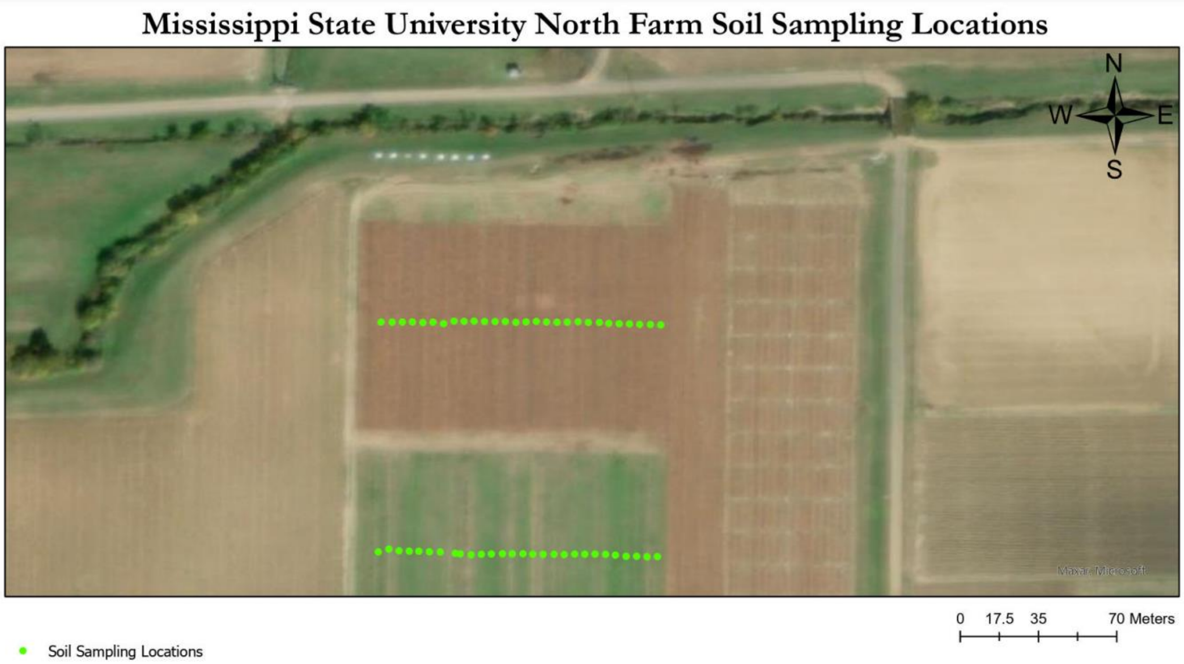

Figure 3.2 Soil sampling points in the study site R.R. Foil Plant Science Research Center, Mississippi State University, MS

Soil Physical Health Indicators

Soil bulk density

The soil bulk density is an indicator of soil compaction and to determine the impact of cover crops on bulk density, we used centrifuge core soil samples with an inner ring diameter of 5.7 cm and length of 5 cm stainless steel core rings. The core ring was pushed into the soil and any excess soil was trimmed from both the edges of the ring. The fresh weight of soil with the ring was recorded first and then was run at different RPMs from 300 till 10000 in a refrigerated high-speed centrifuge and the core rings with the samples were dried at 105 ^{0}C in an oven for 24 hours after recording the weight at 10000 RPM. The dried soil weight was then recorded, and the bulk density is calculated as the dried mass of the soil divided by the volume of the soil.

$$\text{Bulk density} = \frac{\text{Oven dried mass of soil (g)}}{\text{Total volume (cm3)}} \quad (3.2)$$

Saturated hydraulic conductivity (Ksat)

To understand the influence of cover crops on saturated hydraulic conductivity, a constant-head method by Chameleon Automated Ksat 2816, which has the 5 station Chameleon Kit (Soil moisture Equipment Corporation (SEC) 2816GX) was used to obtain measurements. The soil samples were set to saturation for 24 hours before the start of each measurement. Ksat data is generated by precision pressure transducers and the Chameleon Software Application which monitored the pressure head and steady-rate flow over time.

Using Darcy's law (Darcy, 1856), Ksat is estimated by the following equation,

$$K = \left[\frac{aL}{A(t_0 - t_1)}\right] \ln\left(\frac{h_0}{h_1}\right) \quad (3.2)$$

Where, K = saturated hydraulic conductivity ($cm.min^{-1}$);

Q = discharge (cm^3);

$h_0 - h_1$ = difference in hydraulic head

$t_0 - t_1$ = time difference during which $h_0 - h_1$ occurred (min/ hr);

A = cross-sectional area of the sample (cm^2);

L = length of the soil sample (cm).

Soil water retention

The soil water retention parameters such as soil water holding capacity, permanent wilting point and plant available water content were determined using a CR22 N High-Speed Refrigerated Centrifuge (Hitachi, Tokyo, Japan), one of the widely recognized methods to determine the water retention in soil (Reatto et al., 2008 ; Khanzode et al., 2002). The water content at the pressure heads (H=336, H=15310) are calculated by running the centrifuge at different rotations per minute like 300, 650, 850, 950, 1000, 1350, 7000, 9000 and 10000. The mass and the soil compression height of the soil samples were monitored after each RPM and kept in the oven for drying at 105 ^{o} C for at least 24 hours and the obtained dry weights of the samples will be recorded to know the water held by the soil at the desired water potential levels (Feng et al., 2019a). The conversion formula of centrifuge speed and soil pressure head (H).

$$\mathrm{H} = 1.398\mathrm{x}10 - 6\mathrm{n}2[\mathrm{r} - (\mathrm{l} + \mathrm{h})](3\mathrm{r} + \mathrm{l} + \mathrm{h}) \qquad (3.3)$$

Where, H = The corresponding soil suction value at a certain speed (cm);

n = centrifuge speed (r/min);

r = Rotation radius from the centrifuge axis to the bottom of the soil sample (cm);

l = The distance from the centrifuge shaft to the top of the centrifuge box cover (cm);

h = Soil compression height (cm)

The water retention parameters are derived by fitting the obtained parameters into the MATLAB software developed by Van Genuchten (1980). The van Genuchten model is widely used to describe the relationship between volumetric water content (θ_v) and soil water pressure head (ψ).

$$\theta(\psi) = \theta\mathrm{r} + (\theta\mathrm{s} - \theta\mathrm{r})/[1 + (\alpha|\psi|)\mathrm{n}]\mathrm{m} \qquad (3.4)$$

where θs is the saturated volumetric water content, θr is the residual volumetric water content, α is an empirical parameter, which is the inverse of the air entry point or bubbling pressure (cm^{-1}); and *n* is an empirical constant that affects the curve shape (Van Genuchten, 1980; Yates et al., 1992).

Soil Chemical Health Indicators

Soil pH

The soil pH was measured on soil: water (1:1) slurry following the procedure by (Thomas, 1996). Ten grams of air-dried soil sample was weighed into a 50 mL beaker. Ten mL of deionized water was added and mixed well. The soil suspension was allowed to stand for 10 minutes, and soil pH was determined with silver chloride and a combination electrode.

Total Carbon and Total Nitrogen

For total soil carbon and total nitrogen, soil samples were air-dried, ground to pass through 2.00 mm sieve and sent to a commercial laboratory and the measurements were determined using a dry combustion analyzer. Samples were analyzed for total carbon and total nitrogen using an automated dry combustion C/N analyzer (Model NA 1500 NC; Carlo Erba, Milan, Italy) (Adeli et al., 2007) and oxidized above 950 ^{o}C under purified oxygen (Nelson and Sommers, 1996). For this method, samples are weighed in a crucible and introduced to a resistance furnace. Soil sample combustion conducted with O_2 above 950 ^{o}C and converted to CO_2 and N_2, which was detected by a N_2 analyzer and CO_2 detector.

Extractable Macro and Micro-nutrients

The soil samples were air-dried, ground to pass through 2.00 mm sieve the extractable macro- and micro-nutrients like P, K, Mg, Mn, Ca, S, Na and Zn were measured using Mehlich-

3 extraction method. The soil nutrients are extracted with the use of inductively coupled plasma optical emission spectrometry (ICP-OES) along with the Mehlich -3 extractant.

Organic Matter

Soil organic matter is considered as the one of the critical soil health indicators and is measured by calculating the sample weight loss on ignition at 360^{o} C. In general, organic matter can be determined from Total Carbon (TC) content in the soil by multiplying the TC by 1.72.

Cation Exchange Capacity

The cation exchange capacity of a soil is the total negative charge of a soil, or it can be determined by the total number of cations that a soil can hold. CEC was measured using an extraction method where the difference between cation (Ca/Mg/ K) added and amount retained in the solution is calculated to determine the CEC. CEC, in general is measured in milliequivalents per 100 grams of soil (meq/100g).

Soil Health Score

For soil health assessment, we used Soil Management Assessment Framework (SMAF) method, where the Standard Scoring Functions (SSF) based curves were developed for normalizing different health indicators (physical, hydraulic, and chemical) of soil. The SSF curves developed by Karlen and Stott, (1994) characterized the health scores into four curves such as “more is better”, “less is better”, “optimum” and “undesirable range”. Then based on the obtained curves, the soil indicators were converted into a range of unitless, 0 to 1 scores which can be calculated mathematically to make desired comparisons. Principal Component Analysis (PCA) is the type of mathematical tool that was used to obtain the health indicator weights to establish SSF curves. The physical health indicators considered to calculate the health score are bulk density and plant available water content and the chemical health indicators considered to determine the soil health score are soil pH, total carbon, total nitrogen, cation exchange capacity, available phosphorus (P) and extractable potassium content (K). The data values were normalized using the following equation developed by Imam, (1994); Wymore, (1993).

$$Y(a, b, c, S, x) = \frac{1}{1 + \left(\frac{b-a}{x-a}\right)^{2x\,S\,(b+x-2a)}}, x \geq a \text{ and } 0, \qquad x < a \tag{3.5}$$

To determine the SSF curve shape, parameters like a, b, c, and S were determined, where c = upper threshold parameter, b = baseline parameter, a = lower threshold parameter, y = 0.5, x is the soil indicator value, S= slope value at baseline. Once the data was normalized, soil health score was calculated with the mathematical tool PCA using the following equation:

$$\text{Soil Health} = \sum \text{wi x yi} \tag{3.6}$$

where, y = normalized data of soil health indicator, w = weight of each soil health indicator (Chang et al., 2022)

Statistical Analysis

The Analysis of variance (ANOVA) and LSD tests were performed using R studio (version 4.2.2). ANOVA was performed as a Randomized complete block design with one factor (14 cover crop treatments) including the crop rotation sequence (C1 & C2) at $p < 0.05$ using “agricolae” package.

Results and discussion

This field experiment was developed to understand different cover crop strategies under crop rotation. The study focused on effects of different cover crop treatments on soil physical, hydraulic, and chemical health indicators. The data presented was as main effects of 14 cover crop treatments (AC1-GC1 and AC2-GC2), (two cash crop sequences x 7 cover crop treatments = 14 cover crop treatments) on different soil physical and chemical properties at depths 0-5 cm, 5-10 cm, and the soil chemical properties as affected by the cover crop treatments will be discussed at the combined 0-10 cm.

Soil bulk density

Soil bulk density (BD) is an indicator of soil compaction and is determined by calculating the mass of oven-dried soil per volume in an undisturbed state (Magliano et al., 2017) (Fernandez et al 2015). The soil bulk density at the 0-5 and 5-10 cm depths as displayed in Table 3.4 & Table 3.5 tells us that BD was significantly affected by the integration of different cover crop treatments. Cover Crop (CC) treatments such as rye (DC2, FC2), peas (GC2) have potentially reduced the BD by 7.04%, 6.33% and 5.63% respectively in the topsoil (0-5 cm) but at the depth 5-10 cm, rye cover crop treatment (DC1) alone reduced the BD by 6.1% as compared to No Cover Crop (NCC) treatment. Similar findings were observed in the study conducted by Blanco-Canqui et al., (2011) ,who reported the effect of cover crops on bulk density in the surface soil (0-10 cm depth). Also, Villamil et al., (2006) studied the effects of rye and grass cover crop effects in a silty loam soil which resulted in reduced bulk density as compared to no cover crop treatment. Similarly, previous studies by Adeli et al., (2020); Haruna et al., (2018); Sainju et al., (2002) reported that cover crop integration into the cropping systems reduced bulk density by 3, 12 and 3% respectively as compared to no cover crop treatment. After a few years of intensive cultivation practices, the soil becomes susceptible to compaction, breakdown of aggregates significantly degrading the soil health (Koudahe et al., 2022). Bulk density is one of the critical indicators that contributes to soil compaction and it is generally dependent on soil texture, structure, and organic matter of soil (Leifeld et al., 2005; Morisada et al., 2004). Studies by Aşkin and Özdemir, (2003) have reported similar findings stating the interdependent relationships between bulk density and organic matter content under different soil textural classes. In this study, it is observed that the cover crop integration has increased organic matter content in the soil (Figure 3.3) that may have resulted in reduced bulk density.

Saturated hydraulic conductivity (Ksat)

The saturated hydraulic conductivity (Ksat) determines how fast the rainwater percolates into soil. According to the results displayed in Table 3.4. The cover crops did not show any effect on Ksat as compared to the no cover crop treatment at depth 0-5 cm. At the depth 5-10 cm, the Ksat was significantly increased in the plots integrated with the mixture of cover crops (CC2, EC2). In contrast to our results, a 5-year study by Çerçioğlu et al., (2019) reported that cover crop management can result in greater Ksat values. In general, the compacted soil can lead to increased bulk density causing a reduction in Ksat of a soil as it affects the micropore structure in the soil profile (Pagliai et al., 2003). Moreover, some studies suggest that pore distribution plays a key role in determining the Ksat of a soil, as the water retention is high when there is an abundant availability of micropores in the soil consequently increasing the Ksat of a soil (Matthews et al., 2010; Kutilek and Nielsen, 1994). In addition to microporosity, the Ksat is also found to be altered at different depths of soil as shown in Table 3.4, where the Ksat was increased in the subsoil (5-10 cm) when mixture of cover crops were planted but was there no effect of cover crop treatments in the topsoil (0-5 cm). Similar results were recorded by Nakano and Miyazaki, (2005), who observed that Ksat was higher in the subsoil as compared to topsoil implying that compaction can be the reason behind this. The differences in the results were probably due to the length of the cover crop management, soil type, crop rotation practices which can influence the soil structure, proportion of macro and mesopores that facilitate the water movement in the soil.

Soil water retention

Soil water retention parameters include soil water holding capacity/ field capacity (FC), permanent wilting point (PWP) and the plant available water content (PAW). It is believed that soil water content is a critical component that maintains a balance between the crop production and soil water table. Overuse of chemical fertilizers and human induced agricultural practices can lead to soil compaction and reduce the soil water content in the soil profile (Shah et al., 2017). The soil water retention characteristics (FC and PAW) are considered as crucial soil health indicators that help us depict the water potential status of a soil (Saxton and Rawls, 2006) and these factors are found to be strongly influenced by the soil organic matter (Wosten et al., 2019) and textural class (Bauer and Black, 1992). Similar findings were reported by Yang et al., (2015), where the retention capacity of a soil was determined by the organic matter content that differed in different soil textures. In this study, the soil organic matter (Figure 3.3) was found to be increased with the cover crop use and they are found to be correlated with the increase in the plant available water content. As summarized in Table 3.4, the PWP and PAW were significantly affected by the cover crop treatments (AC1- GC1 and AC2 - GC2) in the topsoil (0-5 cm) and in the subsoil (5-10 cm) FC and PWP of the soil were affected but not the PAW (Table 3.5). The mixed cover crop treatment (EC2), and rye (DC2) has significantly increased the PAW by 16% and 11% respectively as compared to NCC (AC2). Similarly, as compared to NCC (AC1), the mixed cover crop treatment (EC1, CC1), and peas (BC1) has significantly increased the PAW by 49%, 36%, and 26% respectively A study conducted by Florence and McGuire, (2020) revealed that similar results where the integration of multi-species cover crops has provided many benefits to soil health by enhancing the soil properties. Similarly, Hubbard et al., (2013) reported that with the integration of cover crops, 18% soil water retention was increased as compared to no cover crop treatment. At the soil depth 5-10 cm, it is observed that the rye cover crop treatment (DC1, FC1), peas (GC1), and mixed (EC1) increased the FC by 12%, 11%, 7.5%, and 6.6% as compared to NCC (AC1). Previous studies by Basche et al., (2016); Villamil et al., (2006) reported that cover crop integration increased the PAW at various depths such as 0-15 cm and 15-30 cm. The cover crop treatments were influenced by the crop rotation sequence (C1 and C2) resulting in a significant impact on water retention parameters at each depth 0-5 cm and 5-10 cm. Furthermore, some studies reported by Rorick and Kladivko, (2017) revealed that cover crops had no significant effect on any soil water retention parameters. The differences in the results can be due to the tillage operations being adopted in the study area for many years and the experiment was conducted under rainfed conditions each year which may have led to destruction in pore size distribution of soil and degraded soil health.

Total carbon and Total nitrogen

Total carbon (TC) was significantly increased by the integration of cover crops at the depth 0-10 cm (Table 3.7). The rye cover crop (FC1) resulted in the highest carbon content in the soil (1.95 %) as compared to other cover crop treatments. Total nitrogen was not affected by crop rotation sequence and cover crops. Similar results with no considerable effects of cover crop on total N were reported by Acuña and Villamil, (2014) at two locations in Illinois. Also, Olson et al., (2010) reported no effect of cover crops on total nitrogen content in an eight-year study. The negative effect of cover crop treatments on TN can be due to the soil compaction that was imposed with changes in the soil structure because of continuous agricultural practices in the study area. In contrast to this, there was a significant increase in the soil organic matter content in the soils integrated with different cover crop treatments. At the depth 0-10 cm, the soils integrated with rye cover crop treatment (FC2) has resulted in the highest organic matter content (1.45 vs 1.23%) followed by DC2 (1.43 vs 1.23%) as compared to NCC. However, to monitor the changes in the soil TC can be challenging under different cropping systems with cover crop integration as it is often difficult to address the minute changes that take place at different depths within the same soil profile and in addition to this, continuous repetition of similar cash crop can restrict the biomass growth of cover crops. These findings are similar to studies conducted by Kaspar et al., (2006) and Duiker and Hartwig, (2004) also reported no significant impact of cover crop mulch on TC and TN content. Cover crop integration, in general, has shown that the biomass produced from the cover crops each year helped in building organic matter in the soil. And our findings suggest that cover crop biomass over the three-year period has improved the organic matter in the subsoil. Rye cover crop (Treatments - D, F) had resulted in higher organic matter in the subsoil as compared to other cover crop treatments. During the first year of cover crop planting, rye crop growth was more as compared to the second year of cover crop planting as the cover crops could not survive the winter in that season. This led to the lower cover crop biomass of all the treatments and there were no significant differences between the treatments in the year 2021. Studies have shown that insufficient accumulation of residues can make soil not responsive to tillage practices which increases the susceptibility to soil erosion and water loss (Nouri et al., 2019b). However, in the year 2022, the cover crops produced greater biomass than all years and among them rye (D) had the greatest biomass (C2 - 9.14 Mg ha^{-1}) followed by peas (B) treatment (C2 - 8.39 Mg ha^{-1}). Similar results were reported by Mirsky et al., (2017) in a 3-year cover crop study which stated that rye has the capacity to produce substantial biomass. Another study by Poffenbarger et al., (2015) revealed that rye produced more biomass than other cover crop species and mixture of cover crops. The season variability, cover crop type, weather conditions can be the possible reasons behind the cover crop growth and biomass production and the accumulation of soil organic matter that led to the minor changes in the formation of aggregates.

Soil pH

The cover crop integration had no significant effect on the soil pH in the topsoil (0-5 cm), subsoil and at the combined depth 0-10 cm Table 3.7). A three-year cover crop study revealed similar results that cover crop did not affect soil pH was reported by Liebig et al., (2015). Similarly, rye cover crop showed no positive effect on soil pH under cotton cropping system in the study conducted by Nyakatawa et al., (2001). Although, at the soil depth 0-10 cm, the rye cover crop treatment (DC1) resulted in higher pH (8.16) as compared to control and other cover crop treatments.

Cation Exchange Capacity

The cation exchange capacity was significantly influenced by the crop rotation sequence (C1 and C2) at depths 0-5, 5-10 cm but there was no effect of cover crop treatments and crop rotation sequence on CEC at the combined depth 0-10 cm (Table 3.6 and Table 3.7). Although cover crops helped in building the organic matter of soil at each depth of soil, there was no positive effect on cation exchange capacity at the depth 0-10 cm. However, from our results, it is observed that the cover crop treatments significantly improved the CEC of soil under cash crop rotation sequence (C1) as compared to the rotation sequence (C2), which tells us that the cover crop integration was certainly affected by the cash crop rotation. Crusciol et al., (2010) reported that CEC is associated with organic matter content and soil nutrient concentration. In addition, they have reported that in the topsoil, a greater amount of organic matter is generated from the cover crop residue each year. Therefore, it seems clear that soil nutrients are altered with the biomass production which also influences the organic matter and CEC (Table 3.7). Each year, the cover crops had a less chance of growing in the cotton plots due to the time of cropping season which can be the reason behind the results.

Extractable macro and micro-nutrients

Among the major nutrients, cover crops showed no significant effect on the phosphorus, and calcium at the depth 0-10 cm (Table 3.9). Although, potassium and magnesium levels were significantly increased at the depth of 0-10 cm under different cover crop treatments. In general, the soils with no treatments had the lowest potassium concentration and it varied from soil that was integrated with cover crop treatments. In our study, at the depth of 0-10 cm, the mixture of cover crop treatments (CC1, CC2) has resulted in higher values of potassium followed by the rye cover crop treatments (FC1, FC2). Our findings were similar to studies conducted by Crusciol et al., (2010), who reported that grasses are highly capable for the accumulation of potassium and Garcia et al., (2008) added that these grass cover crops are known to provide nonexchangeable potassium to the soil which can lead to the reduction in usage of chemical fertilizers. Studies by Cunha et al., (2011); Garcia and Rosolem, (2010) reported that cover crop integration into the soil can aid in biomass production on the soil surface that is correlated with alteration of soil nutrients concentration. Of the micro-nutrients that were measured, sodium and zinc were significantly affected by the cover crops in the topsoil and sodium was alone influenced in the subsoil but at the combined depth 0-10 cm the micronutrients such as zinc, sodium, and manganese were least affected by the addition of cover crops.

Soil Health Score

Soil physical and chemical health scores were obtained after normalizing the data and weight calculation from standard scoring functions (SSF) and principal component analysis (PCA) respectively as summarized in (Table 3.12). The mathematical tool PCA was used to determine the weights and the SSF parameters have been determined using the selected threshold values (upper, lower and baseline threshold values) to normalize the soil physical and chemical health indicators. Similar approaches have been followed by Gelaw et al., (2015); Bhaduri and Purakayastha, (2014); Masto et al., (2007) to obtain the soil health scores. Chang et al., (2022) has reported that SSF is an effective soil health assessment method to differentiate the treatments differences on soil health scores. The impact of different cover crops on soil health indicators is the focus in this study and the assessment method we have used in our study has shown that cover crop use can improve soil health as compared to no cover crop treatment. The principal components of the selected indicators accounted for 61.9%, 16.6%, 8.06% with a cumulative variance of 86.86%. Most chemical health indicators clustered together indicate they are positively correlated and have been positively influenced by the cover crop treatments. It is observed that rye cover crop has significantly improved soil physical and chemical health scores Table 3.13). Although, compared to the topsoil, the subsoil had better soil physical health in the soils integrated with cover crops.

Conclusion

In this study, assessment of elbon rye, daikon radish, and Austrian winter field peas cover crop species on soil physical and soil chemical health indicators under a corn-cotton rotation was evaluated. Several studies have previously demonstrated the significance of cover crop management on soil related benefits. These findings can help us understand how different cover crop treatments affect certain soil health indicators which can result in improved soil health. Results from this study showed that Cover Crops (CC) can significantly reduce bulk density at both soil depths 0-5 and 5-10 cm and saturated hydraulic conductivity was increased in the subsoil. Although there was no significant effect of cover crops on soil water holding capacity/ field capacity (FC) in the topsoil, cover crops such as rye (DC1, FC1) and mixed treatment (EC1) increased the FC by 12%, 11%, and 6.6% respectively as compared to no cover crop treatment (AC1) at 5-10 cm depth. In contrast to this, the plant available water content was increased significantly with the cover crop integration in the subsoil but was not affected in the topsoil. Furthermore, soils with rye and mixture of cover crop treatments increase the total carbon, potassium, and manganese levels respectively at the depth 0-10 cm. At the depth 0-10 cm, the soils integrated with rye cover crop treatment (FC2) has resulted in the highest organic matter content (1.45 vs 1.23%) followed by DC2 (1.43 vs 1.23%) as compared to no cover crop treatment which indicates that cash crop sequence had a significant impact on the organic matter. Along with FC, the cover crops did not show any significant effect on Ksat in the subsoil and at the depth 0-10 cm, total nitrogen (TN), soil pH, cation exchange capacity (CEC), soil pH, a few extractable macro (phosphorus, calcium), and micro-nutrients (sodium, zinc, and manganese) were not affected by the cover crops. The quantification of soil data tells us that the rye and mixture of cover crops could potentially increase both the soil physical and chemical health scores at two soil depths 0-5 and 5-10 cm.

It is important to notice that although we had significant differences among some soil health indicators, these differences, in most soil properties, were the result of only three years of cover crop integration and two years of crop rotation evaluation. It is likely that if we had more years of evaluations, the effect of cover crop treatments would increase the differences between the soil health indicators. However, the potential benefits of cover crops in diversified cropping systems can depend on various factors such as tillage practices, soil type, selection of cover crop (single species or mixture) and nutrient management. Hence, additional field studies are necessary to determine the long-term impact of cover crops to achieve the goal of sustainability in agriculture.

Tables

Table 3.4 Main effects of cover crop treatments under a crop rotation sequence (C1 & C2) on mean bulk density, soil water holding capacity, permanent wilting point, available water content and saturated hydraulic conductivity (Ksat) with p- values at soil depth 0-5 cm.

Cover crop Treatment	Bulk density † g.cm^{-3}	Soil water holding capacity %	Permanent wilting point %	Available water content %	Ksat cm.min^{-1}
AC1 (NCC)	1.39 (0.02) abcd	29.12 (0.7) abc	21.79 (1.4) ab	7.32 (1.1) ef	0.0004 (0.0001) b
AC2 (NCC)	1.42 (0.01) § a	26.94 (1.5) bc	16.89 (1.7) c	10.05 (0.4) abc	0.0125 (0.0001) ab
BC1 (Peas)	1.40 (0.02) abc	28.72 (0.3) abc	19.42 (0.3) abc	9.25 (0.1) bcde	0.0137 (0.0001) ab
BC2 (Peas)	1.35 (0.02) cdef	26.35(0.5) c	16.04 (0.9) c	10.31 (0.4) abc	0.0055 (0.0001) ab
CC1 (Mixed)	1.40 (0.03) abc	30.57 (1.0) abc	20.60 (1.5) abc	9.96 (1.1) abc	0.0006 (0.0001) b
CC2 (Mixed)	1.38 (0.01) abcde	29.68 (1.7) abc	20.20 (2.2) abc	9.47 (0.7) bcd	0.0036 (0.0001) b
DC1 (Rye)	1.38 (0.02) bcdef	30.99 (1.1) ab	23.09 (1.1) a	7.89 (0.6) def	0.0287 (0.0001) a
DC2 (Rye)	1.32 (0.01) f	27.33 (0.8) bc	16.15 (0.7) c	11.18 (0.4) ab	0.0011 (0.0001) b
EC1 (Mixed)	1.39 (0.01) abcd	31.76 (2.7) a	20.85 (2.3) abc	10.91 (0.7) ab	0.0177 (0.0001) a
EC2 (Mixed)	1.37 (0.02) abcdef	28.42 (1.2) abc	16.77 (0.6) c	11.65 (0.8) a	0.0012 (0.0001) b
FC1 (Rye)	1.35 (0.006) cdef	28.72 (3.3) abc	21.85 (4.4) ab	6.86 (1.3) f	0.0085 (0.0001) ab
FC2 (Rye)	1.33 (0.02) ef	27.67 (1.5) abc	17.84 (2.1) bc	9.83 (0.8) abcd	0.0008 (0.0001) b
GC1 (Peas)	1.41 (0.01) ab	28.92 (1.5) abc	20.07 (1.6) abc	8.84 (1.2) cdef	0.0027 (0.0001) b
GC2 (Peas)	1.34 (0.004) f	26.55(0.5) c	16.11 (0.7) c	10.69 (0.3) abc	0.0009 (0.0001) b
P- value	0.01	0.3	0.03	0.0003	0.2

†Variables in column with same letters are not significant at the 0.05 level using Fisher's Protected LSD.

§ Standard error of means in parenthesis.

Table 3.5 Main effects of cover crop treatments under a crop rotation sequence (C1 & C2) on mean bulk density, soil water holding capacity, permanent wilting point, available water content and saturated hydraulic conductivity (Ksat) with p-values at soil depth 5-10 cm.

Cover crop Treatment	**Bulk density †** $g.cm^{-3}$	**Soil water holding capacity** %	**Permanent wilting point** %	**Available water content** %	**Ksat** $cm.min^{-1}$
AC1 (NCC)	1.47 (0.008) abc	27.70 (0.8) bcde	20.23 (1.8) abcd	7.46 (1.0) ∮ c	0.0003 (0.0002) b
AC2 (NCC)	1.47 (0.01) abc	25.14 (0.9) e	16.15 (1.1) ef	8.99 (0.2) abc	0.0055 (0.002) ab
BC1 (Peas)	1.49 (0.009) ab	28.37 (0.4) abcd	19.81 (0.3) abcde	8.55 (0.5) abc	0.0010 (0.0003) b
BC2 (Peas)	1.42 (0.009) cd	25.37 (1.8) de	16.43 (2.1) def	8.94 (0.2) abc	0.0015 (0.0008) b
CC1 (Mixed)	1.45 (0.01) bc	29.29 (1.1) abc	19.85 (1.2) abcde	9.45 (1.1) abc	0.0068 (0.004) ab
CC2 (Mixed)	1.46 (0.02) abc	27.45 (1.5) cde	18.89 (1.4) cdef	8.56 (0.1) abc	0.0115 (0.006) a
DC1 (Rye)	1.38 (0.02) d	30.94 (1.8) a	23.06 (2.7) ab	7.87 (1.0) bc	0.0009 (0.0006) b
DC2 (Rye)	1.43 (0.03) cd	25.40 (0.9) de	15.46 (0.9) f	9.83 (0.2) ab	0.0029 (0.0007) b
EC1 (Mixed)	1.44 (0.01) bcd	29.55 (1.3) abc	19.11 (0.5) bcdef	10.43 (0.8) a	0.0015 (0.0008) b
EC2 (Mixed)	1.47 (0.03) abc	26.74 (0.7) cde	17.11 (0.6) def	9.62 (0.4) ab	0.0115 (0.004) a
FC1 (Rye)	1.42 (0.02) cd	30.79 (0.8) a	23.35 (2.0) a	7.44 (1.1) c	0.0006 (0.0002) b
FC2 (Rye)	1.46 (0.04) abc	25.18 (1.3) e	16.28 (1.8) ef	8.78 (0.6) abc	0.0033 (0.001) b
GC1 (Peas)	1.46 (0.01) abc	29.80 (0.6) abc	21.90 (1.0) abc	7.90 (0.7) bc	0.0010 (0.0006) b
GC2 (Peas)	1.51 (0.02) a	25.85 (0.3) de	16.54 (0.5) def	9.31 (0.2) abc	0.0025 (0.001) b
P- value	0.01	0.0006	0.001	0.15	0.03

†Variables in column with same letters are not significant at the 0.05 level using Fisher's Protected LSD.

∮ Standard error of means in parenthesis.

Table 3.6 Main effects of cover crop treatments under a crop rotation sequence (C1 & C2) on mean total carbon, total nitrogen, soil pH, cation exchange capacity and organic matter with p-values at soil depth 0-5 cm.

Cover crop Treatment	**Total carbon †** **%**	**Total nitrogen** **%**	**Soil pH**	**Cation exchange capacity** **meq/100g**	**Organic matter** **%**
0-5 cm soil depth					
AC1 (NCC)	1.89 (0.07) bcde	0.20 (0.02) ₰ bc	8.02 (0.02) abcd	29.82 (1.26) a	1.31(0.02) de
AC2 (NCC)	1.86 (0.05) cdef	0.21 (0.02) bc	8.02 (0.02) abcd	23.10 (1.34) b	1.30 (0.02) e
BC1 (Peas)	2.02 (0.07) abcd	0.24 (0.07) abc	8.02 (0.07) abcd	30.22 (2.19) a	1.47 (0.02) abcde
BC2 (Peas)	1.74 (0.07) ef	0.31(0.05) a	7.95 (0.05) cd	24.32 (1.38) b	1.32 (0.02) cde
CC1 (Mixed)	2.06 (0.12) abc	0.21(0.02) bc	8.05 (0.02) abcd	31.00 (1.58) a	1.49 (0.02) abcd
CC2 (Mixed)	1.83 (0.07) def	0.25(0.03) abc	8.00 (0.04) bcd	25.00 (2.00) b	1.43(0.02) abcde
DC1 (Rye)	2.10 (0.13) ab	0.25 (0.01) abc	8.15 (0.02) a	31.65 (2.39) a	1.58 (0.02) a
DC2 (Rye)	1.67 (0.04) f	0.17 (0.05) c	8.00 (0.02) bcd	23.65 (1.39) b	1.44 (0.02) abcde
EC1 (Mixed)	2.06 (0.03) abc	0.21 (0.03) bc	8.02 (0.07) abcd	29.10 (1.47) a	1.50 (0.02) abc
EC2 (Mixed)	1.82 (0.08) def	0.29 (0.04) ab	8.07 (0.02) abc	23.07 (1.64) b	1.33 (0.02) cde
FC1 (Rye)	2.14 (0.12) a	0.22 (0.01) bc	8.07 (0.04) abc	29.67 (2.16) a	1.54(0.02) ab
FC2 (Rye)	1.98 (0.08) abcd	0.27 (0.03) abc	7.92 (0.07) d	24.35 (0.71) b	1.54 (0.02) ab
GC1 (Peas)	1.91 (0.06) bcde	0.19 (0.02) bc	8.10 (0.04) ab	30.65 (1.85) a	1.54 (0.02) ab
GC2 (Peas)	1.83 (0.06) def	0.19 (0.04) bc	7.95 (0.06) cd	23.27 (0.80) b	1.36 (0.02) bcde
P- value	<0.0001	0.2	0.1	<0.0001	0.01

†Variables in column with same letters are not significant at the 0.05 level using Fisher's Protected LSD.
₰ Standard error of means in parenthesis.

Table 3.7 Main effects of cover crop treatments under a crop rotation sequence (C1 & C2) on mean total carbon, total nitrogen, and soil pH, cation exchange capacity and organic matter with p-values at soil depth 5-10 cm and at combined depth 0-10 cm.

Cover crop Treatment	Total carbon † %	Total nitrogen %	Soil pH	Cation exchange capacity meq /100 g	Organic matter %
5-10 cm soil depth					
AC1 (NCC)	1.84 (0.11) § ab	0.19 (0.01) a	7.57 (0.4) b	33.90 (3.28) a	1.17 (0.04) cde
AC2 (NCC)	1.65 (0.01) bcde	0.21 (0.02) a	8.10 (0.05) a	25.02 (1.57) b	1.01 (0.02) f
BC1 (Peas)	1.78 (0.09) abc	0.19 (0.006) a	8.12 (0.04) a	31.30 (2.42) a	1.33 (0.02) a
BC2 (Peas)	1.57 (0.06) de	0.21 (0.04) a	8.17 (0.02) a	25.00 (1.41) b	0.98 (0.03) f
CC1 (Mixed)	1.84 (0.14) ab	0.20 (0.007) a	8.12 (0.02) a	33.55 (3.30) a	1.31 (0.04) abc
CC2 (Mixed)	1.77 (0.07) abcd	0.21 (0.04) a	8.20 (0.00) a	26.52 (1.78) b	1.17 (0.10) cde
DC1 (Rye)	1.94 (0.09) a	0.19 (0.02) a	8.20 (0.00) a	34.20 (3.02) a	1.42 (0.03) a
DC2 (Rye)	1.60 (0.08) cde	0.19 (0.03) a	8.20 (0.00) a	25.17 (1.01) b	1.06 (0.02) def
EC1 (Mixed)	1.89 (0.08) a	0.23 (0.02) a	8.02 (0.11) a	31.30 (0.94) a	1.35 (0.07) ab
EC2 (Mixed)	1.55 (0.03) e	0.23 (0.02) a	8.20 (0.04) a	25.05 (1.38) b	1.05 (0.12) ef
FC1 (Rye)	1.92 (0.10) a	0.20 (0.01) a	8.20 (0.00) a	30.87 (1.91) b	1.36 (0.02) a
FC2 (Rye)	1.65 (0.06) bcde	0.20 (0.04) a	8.15 (0.02) a	26.00 (0.97) b	1.20 (0.09) bcd
GC1 (Peas)	1.81 (0.03) ab	0.23 (0.007) a	8.20 (0.00) a	33.55 (2.45) a	1.27 (0.07) abc
GC2 (Peas)	1.54 (0.04) e	0.20 (0.03) a	8.22 (0.02) a	25.00 (0.92) b	1.01 (0.06) f
P- value	0.0003	0.99	0.07	<0.0001	<0.0001
0-10 cm soil depth					
AC1 (NCC)	1.77 (0.04) cd	0.20 (0.005) ab	8.06 (0.03) a	27.42 (1.08) ab	1.16 (0.02) g
AC2 (NCC)	1.85 (0.05) abc	0.20 (0.003) ab	7.80 (0.22) b	28.50 (2.10) ab	1.23 (0.02) efg
BC1 (Peas)	1.80 (0.02) bcd	0.22 (0.02) a	8.10 (0.05) a	27.61 (1.75) ab	1.23 (0.01) fg
BC2 (Peas)	1.76 (0.04) cd	0.25 (0.03) a	8.03 (0.04) a	27.81 (1.75) ab	1.33 (0.02) cde
CC1 (Mixed)	1.91 (0.05) ab	0.21 (0.02) ab	8.12 (0.01) a	28.76 (1.63) ab	1.33 (0.06) cde
CC2 (Mixed)	1.83 (0.10) abcd	0.22 (0.01) ab	8.06 (0.02) a	29.27 (2.54) a	1.37 (0.06) abc
DC1 (Rye)	1.85 (0.08) abcd	0.22 (0.01) ab	8.17 (0.01) a	28.41 (1.55) ab	1.32 (0.03) cdef
DC2 (Rye)	1.80 (0.06) bcd	0.18 (0.03) b	8.10 (0.01) a	28.92 (1.96) ab	1.43 (0.03) ab
EC1 (Mixed)	1.80 (0.02) bcd	0.22 (0.02) ab	8.11 (0.05) a	27.07 (0.87) b	1.28 (0.08) cdef
EC2 (Mixed)	1.85 (0.06) abc	0.26 (0.03) a	8.05 (0.06) a	27.18 (1.07) b	1.34 (0.06) bcd
FC1 (Rye)	1.90 (0.09) ab	0.21 (0.02) ab	8.11 (0.03) a	27.83 (1.43) ab	1.37 (0.04) abcd
FC2 (Rye)	1.95 (0.08) a	0.23 (0.01) ab	8.06 (0.03) a	27.61 (1.12) ab	1.45 (0.05) a
GC1 (Peas)	1.72 (0.05) d	0.20 (0.02) ab	8.16 (0.02) a	27.82 (1.32) ab	1.27 (0.04) def
GC2 (Peas)	1.82 (0.02) bcd	0.21 (0.02) ab	8.07 (0.03) a	28.41 (1.58) ab	1.32 (0.02) cdef
P- value	0.04	0.65	0.12	0.5	<0.0001

†Variables in column with same letters are not significant at the 0.05 level using Fisher's Protected LSD.

§ Standard error of means in parenthesis.

Table 3.8 Main effects of cover crop treatments under a crop rotation sequence (C1 & C2) on mean soil chemical health indicators such as available Phosphorus (P), extractable Potassium (K), Magnesium (Mg), and Calcium (Ca) in mg kg^{-1} under with p-values at soil depth 0-5 cm.

Cover crop Treatment	**P †**	**K**	**Mg**	**Ca**
0-5 cm soil depth				
AC1 (NCC)	85.000 (6.88) ∮ bc	210.75 (10.6) ab	83.25 (3.37) bcd	5615.00 (249.0) a
AC2 (NCC)	85.620 (8.75) bc	207.25 (16.1) b	86.37 (2.55) bcd	4265.87 (274.0) b
BC1 (Peas)	87.120 (6.65) bc	219.75 (25.1) ab	89.87 (4.86) abcd	5670.12 (445.0) a
BC2 (Peas)	85.620 (3.64) bc	227.75 (16.0) ab	83.50 (1.84) bcd	4507.25 (269.0) b
CC1 (Mixed)	114.62 (10.0) ab	260.87 (10.7) a	102.87 (4.10) a	5776.50 (305.0) a
CC2 (Mixed)	102.25 (5.98) abc	260.50 (20.5) a	95.25 (9.47) abc	4606.75 (376.0) b
DC1 (Rye)	123.87 (26.2) a	239.12 (15.1) ab	93.12 (6.36) abc	5949.12 (458.0) a
DC2 (Rye)	76.870 (7.85) c	192.37 (16.5) b	75.50 (5.53) d	4410.37 (272.0) b
EC1 (Mixed)	103.25 (1.23) abc	239.12 (7.03) ab	98.00 (4.78) abc	5425.00 (290.0) a
EC2 (Mixed)	90.620 (2.21) bc	206.75 (9.09) b	82.37 (4.63) cd	4269.12 (314.0) b
FC1 (Rye)	95.370 (10.4) abc	225.50 (22.2) ab	89.87 (6.03) abcd	5560.50 (408.0) a
FC2 (Rye)	108.87 (19.4) ab	240.75 (25.3) ab	98.75 (8.64) ab	4477.50 (135.0) b
GC1 (Peas)	76.870 (9.05) c	214.87 (36.8) ab	95.25 (10.6) abc	5768.87 (343.0) a
GC2 (Peas)	113.87 (8.36) ab	242.00 (11.5) ab	92.62 (2.44) abc	4278.50 (155.0) b
P - value	0.09	0.2	0.06	<0.0001

†Variables in column with same letters are not significant at the 0.05 level using Fisher's Protected LSD.

∮ Standard error of means in parenthesis.

Table 3.9 Main effects of cover crop treatments under a crop rotation sequence (C1 & C2) on mean soil chemical health indicators such as Manganese (Mn), Sodium (Na) and Zinc (Zn) in mg kg^{-1} with p-values at soil depth 0-5 cm.

Cover crop Treatment	**Mn †**	**Na**	**Zn**
0-5cm depth			
AC1 (NCC)	49.00 (3.01) § a	30.12 (1.31) bcd	3.46 (0.25) cd
AC2 (NCC)	42.75 (2.75) bcd	22.50 (2.48) e	3.82 (0.26) bcd
BC1 (Peas)	45.50 (3.26) abc	33.87 (3.30) abc	3.97 (0.30) abcd
BC2 (Peas)	46.25 (2.63) abc	25.87 (1.95) de	3.56 (0.26) cd
CC1 (Mixed)	41.37 (2.00) bcd	39.62 (5.56) a	5.01 (0.31) ab
CC2 (Mixed)	47.12 (2.63) ab	25.50 (4.35) de	3.83 (0.29) bcd
DC1 (Rye)	42.87 (2.30) abcd	36.87 (4.23) ab	5.30 (1.04) a
DC2 (Rye)	40.62 (1.42) cd	22.50 (1.32) e	2.85 (0.26) d
EC1 (Mixed)	40.50 (2.80) cd	37.12 (0.85) a	4.56 (0.33) abc
EC2 (Mixed)	41.12 (2.51) bcd	21.37 (1.77) e	3.46 (0.09) cd
FC1 (Rye)	38.87 (2.95) d	35.12 (2.49) abc	3.76 (0.35) bcd
FC2 (Rye)	46.00 (1.31) abc	23.50 (2.88) de	4.70 (0.89) abc
GC1 (Peas)	43.62 (1.57) abcd	30.00 (1.76) cd	3.81 (0.53) bcd
GC2 (Peas)	44.12 (2.42) abcd	23.62 (2.20) de	4.16 (0.36) abcd
P- value	0.07	<0.0001	0.05

†Variables in the column with the same letter are not significant at the 0.05 level using Fisher's protected LSD.

§ Standard error of means in parenthesis.

Table 3.10 Main effects of cover crop treatments under a crop rotation sequence (C1 & C2) on mean soil chemical health indicators such as P, K, Mg, and Ca in mg kg^{-1} with p-values at soil depth 5-10 cm and at combined depth 0-10 cm.

Cover crop treatment	Phosphorus †	Potassium	Magnesium	Calcium
5-10cm depth				
AC1 (NCC)	58.62 (3.89) ₰ a	142.87 (11.1) bc	59.00 (5.22) ab	6163.37 (562.3) ab
AC2 (NCC)	52.75 (2.40) a	135.00 (4.68) bc	41.01 (13.0) c	3337.25 (1099.2) f
BC1 (Peas)	59.50 (2.44) a	161.62 (22.3) abc	65.00 (4.14) ab	5964.50 (474.6) abcd
BC2 (Peas)	49.50 (1.62) a	121.87 (8.75) c	50.87 (1.93) bc	4757.50 (276.9) cde
CC1 (Mixed)	55.50 (3.93) a	153.37 (1.25) bc	66.37 (4.60) ab	6409.37 (651.1) a
CC2 (Mixed)	57.62 (6.53) a	202.75 (34.8) a	63.50 (3.25) ab	4994.50 (361.4) bcde
DC1 (Rye)	60.12 (7.37) a	148.87 (10.9) bc	67.25 (5.06) a	6539.50 (590.6) a
DC2 (Rye)	46.25 (5.01) a	139.97 (14.5) bc	57.62 (5.78) ab	4762.00 (203.7) cde
EC1 (Mixed)	55.50 (4.11) a	142.50 (9.85) bc	63.62 (5.77) ab	5976.00 (178.2) abc
EC2 (Mixed)	47.12 (1.74) a	149.50 (7.66) bc	58.75 (3.76) ab	4733.87 (272.7) de
FC1 (Rye)	61.12 (13.1) a	147.75 (11.5) bc	61.62 (5.78) ab	5890.00 (378.7) abcde
FC2 (Rye)	62.62 (12.1) a	169.87 (29.3) ab	62.52 (7.09) ab	4898.87 (185.9) cde
GC1 (Peas)	49.50 (4.81) a	145.12 (11.8) bc	65.00 (4.80) ab	6428.12 (480.6) a
GC2 (Peas)	54.87 (4.59) a	152.50 (7.52) bc	58.62 (3.91) ab	4730.37 (179.3) e
P- value	0.68	0.23	0.11	<0.0001
0-10cm depth				
AC1 (NCC)	68.87 (3.34) bcd	172.87 (6.37) c	62.13 (5.49) c	4476.12 (560.4) b
AC2 (NCC)	77.87 (2.68) abcd	175.06 (10.8) c	72.68 (2.20) abc	5214.62 (320.6) a
BC1 (Peas)	68.31 (2.82) d	170.81 (13.5) c	70.37 (2.40) bc	5213.81 (350.7) a
BC2 (Peas)	72.56 (0.60) abcd	194.68 (11.7) bc	74.25 (2.87) ab	5235.87 (345.3) a
CC1 (Mixed)	86.12 (5.92) a	231.81 (12.8) a	83.18 (3.67) a	5385.50 (324.7) a
CC2 (Mixed)	78.87 (4.50) abcd	206.93 (10.6) ab	80.81 (6.99) ab	5508.06 (495.5) a
DC1 (Rye)	85.06 (11.1) ab	179.31 (7.86) bc	75.37 (4.10) ab	5355.56 (299.7) a
DC2 (Rye)	68.50 (2.11) bcd	170.62 (6.66) c	71.37 (2.51) bc	5474.93 (386.8) a
EC1 (Mixed)	75.18 (1.34) abcd	194.31 (7.30) bc	78.37 (1.60) ab	5079.43 (176.1) ab
EC2 (Mixed)	73.06 (2.00) abcd	174.62 (7.97) c	73.00 (4.12) ab	5122.56 (202.3) ab
FC1 (Rye)	79.00 (6.85) abcd	197.68 (11.2) bc	77.75 (4.61) ab	5228.68 (277.7) a
FC2 (Rye)	85.00 (13.2) abc	194.25 (13.3) bc	80.18 (5.15) ab	5183.75 (224.4) a
GC1 (Peas)	65.87 (6.34) d	183.68 (20.9) bc	72.25 (7.06) bc	5249.62 (248.3) a
GC2 (Peas)	81.68 (6.41) abcd	193.56 (9.22) bc	78.81 (3.21) ab	5353.31 (309.1) a
P- value	0.2	0.01	0.03	0.3

†Variables in column with same letters are not significant at the 0.05 level using Fisher's Protected LSD.

₰ Standard error of means in parenthesis.

Table 3.11 Main effects of cover crop treatments under a crop rotation sequence (C1 & C2) on mean soil chemical health indicators such as Manganese (Mn), Sodium (Na) and Zinc (Zn) in mg kg^{-1} with p-values at soil depth 5 -10 cm and at combined depth 0-10 cm.

Cover crop Treatment	**Mn †**	**Na**	**Zn**
5-10 cm depth			
AC1 (NCC)	47.62 (2.46) ≬ a	29.12 (1.65) ab	2.23 (0.13) b
AC2 (NCC)	31.98 (10.2) b	21.75 (1.33) c	7.80 (5.74) a
BC1 (Peas)	46.50 (1.77) a	29.00 (2.07) ab	2.45 (0.05) b
BC2 (Peas)	43.75 (1.93) a	24.25 (1.42) c	1.88 (0.12) b
CC1 (Mixed)	42.50 (2.13) a	31.37 (2.14) a	2.07 (0.08) b
CC2 (Mixed)	45.75 (2.13) a	25.75 (3.19) bc	2.10 (0.13) b
DC1 (Rye)	39.12 (1.92) ab	32.65 (0.94) a	2.46 (0.15) b
DC2 (Rye)	41.12 (1.72) ab	23.00 (1.55) c	1.82 (0.16) b
EC1 (Mixed)	40.87 (0.82) ab	31.00 (1.49) a	2.37 (0.34) b
EC2 (Mixed)	42.50 (2.06) a	22.50 (1.62) c	1.70 (0.07) b
FC1 (Rye)	39.37 (2.29) ab	32.00 (1.65) a	2.37 (0.41) b
FC2 (Rye)	45.37 (1.33) a	24.12 (2.95) c	2.37 (0.43) b
GC1 (Peas)	39.62 (0.65) ab	29.75 (0.82) ab	2.07 (0.14) b
GC2 (Peas)	40.12 (1.95) ab	24.12 (0.94) c	1.97 (0.11) b
P- value	0.2	<0.0001	0.47
0-10 cm depth			
AC1 (NCC)	40.49 (4.09) b	25.93 (1.23) b	5.63 (2.98) a
AC2 (NCC)	45.18 (2.40) ab	25.81 (2.02) b	3.03 (0.12) b
BC1 (Peas)	44.62 (2.56) ab	29.06 (2.30) ab	2.93 (0.19) b
BC2 (Peas)	46.37 (2.05) a	27.43 (1.98) b	3.00 (0.13) b
CC1 (Mixed)	43.56 (0.93) ab	32.68 (4.23) a	3.55 (0.20) ab
CC2 (Mixed)	44.81 (2.34) ab	28.43 (3.16) ab	2.95 (0.16) b
DC1 (Rye)	42.00 (1.45) ab	29.93 (1.83) ab	3.56 (0.43) ab
DC2 (Rye)	39.87 (1.24) b	27.56 (0.35) b	2.65 (0.07) b
EC1 (Mixed)	41.50 (2.11) ab	29.81 (0.61) ab	3.13 (0.14) b
EC2 (Mixed)	41.00 (1.66) ab	26.18 (1.02) b	2.91 (0.16) b
FC1 (Rye)	42.12 (1.65) ab	29.62 (2.49) ab	3.06 (0.25) b
FC2 (Rye)	42.68 (0.65) ab	27.75 (2.14) b	3.53 (0.51) ab
GC1 (Peas)	41.87 (0.31) ab	27.06 (0.59) b	2.89 (0.26) b
GC2 (Peas)	41.87 (1.16) ab	26.68 (1.12) b	3.11 (0.23) b
P- value	0.4	0.1	0.6

†Variables in column with same letters are not significant at the 0.05 level using Fisher's Protected LSD.

≬ Standard error of means in parenthesis.

Table 3.12 Normalized soil physical and chemical health indicators data by the method SSF (Standard Scoring Functions).

	Physical health indicators		**Chemical health indicators**					
Treatments	BD	AWC	TC	TN	pH	CEC	P	K
0-5 cm depth								
NCC	0.47	0.041	0.943	0.939	0.04	0.9	0.57	0.37
Peas	0.55	0.049	0.939	0.740	0.04	0.9	0.58	0.44
Rye	0.63	0.042	0.947	0.903	0.04	0.9	0.61	0.42
Mixed	0.52	0.065	0.902	0.870	0.04	0.9	0.71	0.50
5-10 cm depth								
NCC	0.32	0.030	0.906	0.938	0.16	0.9	0.21	0.15
Peas	0.32	0.030	0.880	0.902	0.02	0.9	0.19	0.17
Rye	0.44	0.035	0.906	0.885	0.01	0.9	0.23	0.19
Mixed	0.40	0.045	0.903	0.938	0.02	0.9	0.22	0.18

Note: BD = Bulk Density, AWC = Available water content, TC = Total Carbon, TN = Total Nitrogen, CEC = Cation Exchange Capacity, P = Phosphorus, K = Potassium

Table 3.13 Soil physical, chemical, and overall health scores determined from SMAF (Soil Management Assessment Framework) based on SSF (Standard Scoring Function) values and PCA (Principal Component Analysis) weights of cover crop treatments and indication of soil health level at two soil depths 0-5 and 5-10 cm.

Treatments	Soil Physical Health Score	Soil Chemical Health Score	Overall Soil Health Score	Soil Health Level
0-5 cm depth				
NCC	20.58	73.98	47.28	medium
Peas	23.98	72.93	48.45	medium
Rye	26.60	74.52	50.56	medium
Mixed	24.01	74.50	49.25	medium
5-10 cm depth				
NCC	11.79	71.61	41.70	medium
Peas	11.92	71.30	41.61	medium
Rye	15.67	72.51	44.09	medium
Mixed	14.07	73.37	43.72	medium

Note: 0-20: very low; 20-40: low; 40-60: medium; 60-80: high; 80-100: very high

Figures

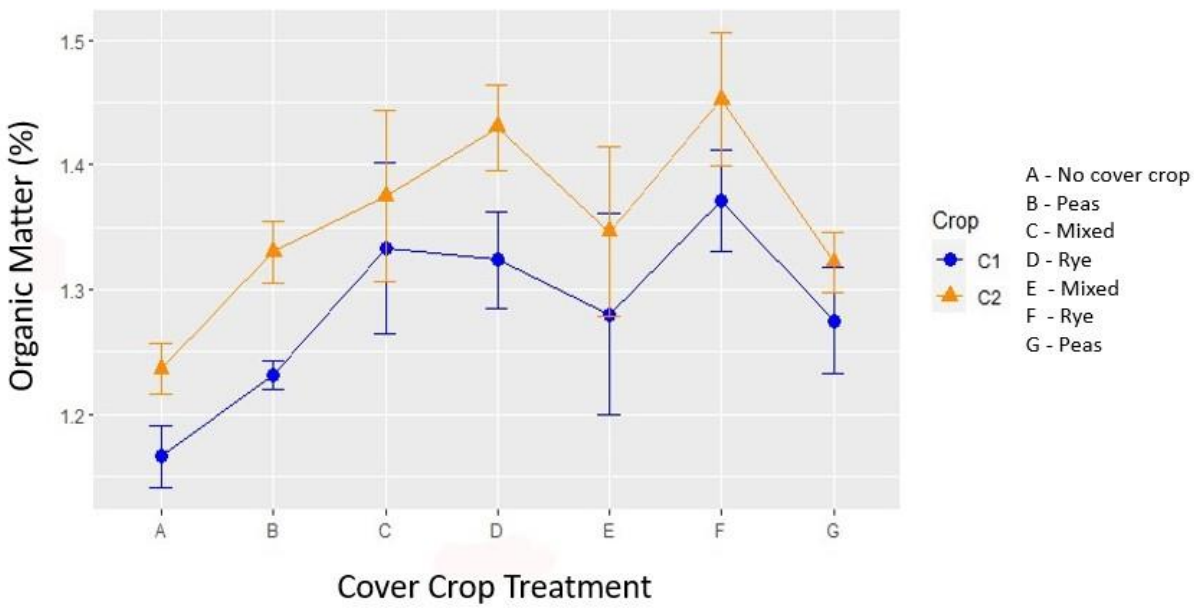

Figure 3.3 Effect of cover crop treatments under the crop rotation sequence (C1 and C2) on organic matter (%) at the soil depth 0-10 cm.

CHAPTER IV

SUMMARY AND CONCLUSION

Integration of cover crops into fallow places in existing cropping systems is considered as a potential management practice to rejuvenate degraded soil health. Along with the cover cropping, use of organic amendments such as poultry litter (PL) is another beneficial practice adopted by many producers across the world. These conservation management practices have caught the most attention in recent years for their benefits towards soil health and crop production. Although cover crops and PL have the potential to improve soil properties, enhance crop productivity and reduce the intake of chemical fertilizers, they are not thoroughly practiced in most agricultural systems due to lack of management information, enough cover crop seed, knowledge on benefits resulting from following the practices. Therefore, there is a need to investigate the potential benefits of these management practices that can be utilized by farmers assured with financial incentives and to achieve this, long-term studies on cover crop and PL impacts towards soil health have become necessary. Two field experiments evaluating the effects of different cover crop species and poultry manure application on soil physical, hydraulic, and chemical health indicators with different soil types under different cropping systems were established for this study. The results obtained from the data collection tell us that we had significant differences among some soil health indicators, these differences, in most soil properties, were comparatively low as it was the result of only a few years of management practices. It is likely that if we had more years of evaluations, the effect of cover crop treatments would increase the differences between the soil health indicators in the North-Central Mississippi region.

In the Pontotoc study site, our results show that the soils with cover crops like winter wheat and cereal rye mixed with mustard increased the SWC by 3.15% and 4.17% in depths 0-5 and 5-10 cm respectively. Cover crop management has also resulted in increased Ksat content due to the presence of macro and mesopores, which has led to high water retention, high infiltration rate and reduced soil erosion. This is evident from our results which suggest that as compared to no cover crop treatment, cereal rye decreased the BD by 5.14%. The cover crop integration affected the chemical indicators like soil pH, CEC, and Total Carbon (TC) content but did not show much effect on other indicators. In the soil depth 0-10 cm, CC like cereal rye and rye mixed with mustard has increased the TC by 3.4% and 14.5% respectively and CEC was found to be increased by 15.9% with the integration of vetch cover crop. PL, on other hand, has potentially increased the carbon content by 11% which resulted in high organic matter in the soil as compared to control. Litter, being a substantial source of nutrients when applied in the soil, created a reservoir of nutrients which can be utilized by the following crop. Results indicated that five years of PL application tremendously increased the Ca, Mg, K, S, Zn, and P by 4.4%, 27.06%, 47%, 250%, 262% and 538% respectively as compared to no fertilizer treatment. In general, PL is enriched with P content that is strongly correlated with the trace elements availability in the soil especially Zn and Cu. The nutrient enrichment is in general linked with the soil structure and texture that has been improved with the PL application over the period. Our results show that the soils amended with the manure has reduced the BD by 5% at both soil depths 0-5 and 5-10 cm and increased the AWC by 1.2% in 0-5 cm and by 27% in 5-10 cm.

In the North Farm study site, the cover crop management has resulted in different soil responses based on the crop rotation sequence (C1 and C2). For example, At the depth 0-10 cm, the soils integrated with rye cover crop treatment (FC2) has resulted in the highest organic matter content (1.45 vs 1.23%) followed by DC2 (1.43 vs 1.23%) as compared to no cover crop (AC2). Furthermore, soils with rye and mixture of cover crop treatments increase the total carbon, potassium, and manganese levels respectively at the depth 0-10 cm but soil chemical health indicators such as total nitrogen (TN), soil pH, cation exchange capacity (CEC), soil pH, a few extractable macro (phosphorus, calcium), and micro-nutrients (sodium, zinc, and manganese) were not affected by the cover crops. Cover crops when planted in soil, provides a soil cover that helps in conservation of soil moisture facilitating nutrient cycling. Supporting this trend, our results show that at the soil depth 0-5 cm, the mixed cover crop treatment (EC2), and rye (DC2) has significantly increased the PAW by 16% and 11% respectively as compared to NCC (AC2). Similarly, as compared to NCC (AC1), the mixed cover crop treatment (EC1, CC1), and peas (BC1) has significantly increased the PAW by 49%, 36%, and 26% respectively. The difference in soil responses towards crop sequence can be due to the time of cover crop planting as the cotton crop is grown in late spring and has a better chance of utilizing the cover crop benefits as compared to the corn crop. In addition to PAW, cover crop integration has also decreased bulk density resulting in change of soil structure and improved soil health. Cover Crop treatments such as rye (DC2, FC2), peas (GC2) have potentially reduced the BD by 7.04%, 6.33% and 5.63% respectively in the topsoil (0-5 cm) but at the depth 5-10 cm, rye cover crop treatment (DC1) alone reduced the BD by 6.1% as compared to No Cover Crop (NCC).

Overall, cover crops like wheat, cereal rye, elbon rye and the mixture of cover crop species (rye + peas + radish) have been found to be beneficial towards soil health indicators and resulted in improved soil physical and chemical health scores as compared to control treatments. It is understood that combination of different conservation practices such as no-tillage, organic manure, cover crop use can result in better soil health than single practice alone. More research on interaction between the cover crops and poultry litter can help farmers to adopt these management strategies that can prevent soil erosion and improve soil productivity. In our studies, we have observed changes in the soil properties with a few years of cover crop integration, in general, substantial changes can be expected with additional long-term studies of cover crops to achieve the goal of reducing soil erosion, increasing water conservation, and sustaining agriculture leading to improved soil health when practiced for at least 5 years of time or more.

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