IMPACTS OF A WHITE CLOVER 'LIVING MULCH' ON SOIL HEALTH AND FERTILITY IN SOME GEORGIA CROPPING SYSTEMS

by

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(Under the Direction of Matthew Levi)

ABSTRACT

Improving soil health is analogous to improving soil function and is measured with soil properties sensitive to management changes. Cover cropping is a management practice that is increasing in popularity but commonly done with annual cover crops. A perennial cover crop provides a longer time throughout the year for soil change to occur than annual cover crops. Perennial cover crops also adhere to several principles of soil health outlined by USDA-NRCS including keeping the ground covered, maintaining living roots, and increasing the plant diversity. This multi-pronged research was conducted to l) Understand the impacts of perennial and annual cover crops on soil physical and chemical properties over time, 2) Explore the utility of pedotransfer functions to predict hard-to-measure soil properties from soil properties that are relatively easier to obtain, and 3) Quantify nutrient cycling dynamics in perennial cover cropping system. The specific perennial cover crop focused on in this dissertation was white clover (Trifolium repens var. ‘Durana’) often referred to as a ‘living mulch’ (LM). There were several benefits from the LM system including greater mineralizable nitrogen rates than other cover cropping systems. Living mulch acted as a nutrient reservoir for potassium that could be luxury consumed when the cash crop didn’t need the nutrients and later released at critical growth stages. Total organic carbon at the 0-5 cm depth increased in the soil at an average rate of 0.12% per year, as averaged from all trials. At the pecan orchard site, infiltration rates between wheel tracks were 15 cm hr^{-1} faster than in wheel tracks, but the overall infiltration rate decreased in the wheel track area over time. Linear models developed for soils from two regions in Georgia to predict available water content, wilting point, and field capacity performed better than more geographically generalized pedotransfer function models. The LM system can provide many services to producers, but proper management of LM is needed along with sufficient time to realize these benefits.

INDEX WORDS: Soil Health, Living Mulch, Total Organic Carbon, Water Infiltration Rate, Nutrient Reservoir, Potassium

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DEDICATION

This dissertation is dedicated to my son Arthur and my wife Maria.

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CHAPTER 1

INTRODUCTION

Explanation of Dissertation Format

This dissertation comprises six chapters. Chapter one presents an overarching literature review and frames the research problems addressed in the subsequent chapters. Chapters two through five present the core experimental work. An overall conclusion (Chapter six) ties together the findings of chapters two through five and Appendix A presents soil profile descriptions and laboratory data for complete soil profiles representing study sites.

Chapters two and three focus on the impacts of the living mulch system, a perennial cover crop, on soil health metrics over time for two physiographic regions in Georgia. Chapter four compiles data collected from chapters two and three to develop pedotransfer functions for predicting hydraulic properties from physical and chemical properties. Chapter five presents a detailed evaluation of nutrient cycling in a living mulch system for macro and micro-nutrients other than carbon or nitrogen focused on the reproductive growth stages of cotton.

Literature Review

Soils support many things including food production, water purification/regulation, nutrient cycling, etc.; however, many soils worldwide are considered degraded (Jie et al., 2002). To better understand soil conditions and determine whether soil functions are improving or declining, it is necessary to have some metrics to quantify soil change. Perhaps the most promising method for documenting soil change is through soil health measurements. Soil health is defined as the capacity of soil to function as a living ecosystem that sustains plants, animals, and humans (USDA, 2021). Land management is a major factor in controlling soil change and is especially important in agricultural systems (Blanco-Canqui & Ruis 2020; Chalise et al., 2019; Delaune et al., 2019; Nouri et al., 2019). The use of cover crops and reduced tillage collectively account for some of the most notable improvements in soil health for agronomic management systems. This introduction provides context for soil health measurements, various benefits of annual and perennial cover crops, and the application of tools such as pedotransfer functions to help predict soil health properties that are time-consuming and difficult to measure.

Recent work has focused on the use of perennial cover crops for the improvement of important agriculture goals in Georgia (Andrews et al., 2018; Hill et al., 2021; Sanders et al., 2018; Sanders et al., 2017; Weisberger et al., 2024) and outside of Georgia in Tennessee (Quinby et al., 2023a; Quinby et al., 2023b). Oftentimes, these goals of improvements from cover cropping are placed under a broad term of soil health. Soil health can be divided into subsequent areas that can be categorized by biological, chemical, and physical information. The use of cover crops to change soil health has primarily focused on annual cover crops (Decker et al., 2022; Chalise et al., 2019; Nouri et al., 2019). Still, perennial cover crops have the ability to impact soils year-round more directly as opposed to the more seasonal nature of annual cover crops. Physical, hydraulic, and chemical soil properties are closely related to soil organic carbon (SOC) with many feedback loops. For example, increasing SOC can alter soil structure and aggregation, leading to changes in hydraulic conductivity rates (Chalise et al., 2019; Rankoth et al., 2021). Other connections between factors of soil health can be used to estimate other properties that are more costly and time-intensive to analyze but are indicators of matrices of soil health changing. Encompassing many aspects of soil health, the use of cover crops to reach these goals is of interest. Measuring soil properties that are indicators of change can take time to see effects. Time and labor also affect the possibility of understanding changes because both can create limiting factors for studying changes. Using equations for prediction displays the most impactful measurements affected by management choices. The models can aid in selecting measurements to inform about what other properties will be affected by changes in soil health indicators.

Concepts of Soil Health

Soil health captures many of the same concepts as soil quality, defined as the ability of soils to function as it relates to increasing or maintaining plant, animal, air, and water quality (Doran & Zeiss, 2000). Many parameters have been used to measure soil health and have been linked to an increase in soil function. Indicators of soil health vary among sources, but common parameters used to measure soil health include soil pH, Mehlich 1 extractible nutrients, total carbon (C) and nitrogen (N), mineralizable C and N, soil texture, aggregate stability, bulk density, water holding capacity, and saturated hydraulic conductivity (Doran et al., 1996; Kibblewhite et al., 2008; Norris et al., 2020; O'Neill et al., 2021). The Soil Health Institute is a nonprofit organization dedicated to studying soil health and provides a comprehensive list of associated methods (Norris et al., 2020). Additionally, there have been several attempts to calculate soil health scores based on a consistent set of measured values. One of the most common is the soil health assessment made by Cornell University, which comprises 12 primary measurements with some regional factors worked in to give a final score between 0 and 100% (Moebius-Clune et al., 2017). The regions used by the Cornell assessment at that time did not include the Southeastern United States. Another metric of soil health is the Haney test which uses soil chemical and biological indicators to calculate a soil health score, however it lacks soil physical property information (Haney et al., 2018). Evaluating soil health measurements and finding a minimum suite of indices across North America is one goal of the Soil Health Institute (Bagnall et al., 2023). Cost, availability, non-redundant measurements, responsive soil health principles, and conductive to covering scale were key to selecting indications for a minimum dataset. They identified three indicators including aggregate stability, a 24-h C mineralization potential, and soil organic C concentration that met these criteria while still being able to be scaled across North America (Bagnall et al., 2023). The Bagnall et al. (2023) model was not as detailed as a regional-specific method of soil health that has more indicators, but it is noted by their different goals for assessment results that used different indicators. Additional indicators like hydraulic parameters are often added to assess soil health, but the difficulty of sampling and analysis leads to the use of other indicators of hydraulic function through chemical and physical indicators (Bagnall, et al., 2022b). The utilization of PTFs to estimate hydraulic function can be used to reduce in the time and labor needed for some hydraulic measurements that producers desire (Patil & Singh, 2016). Soil organic C interacts with many aspects of soil function and is a key property to compliment physical soil property measurements for estimating a soil's hydraulic function (Bagnall, et al., 2022b). USDA also uses soil health indices and has moved away from using a single score, as this cannot be easy and ubiquitous across areas to interpret soil change (Stott, 2019). The utilization of sensitive indicators provides necessary information to improve soil health and assess the soil function. The issue of using different measurements in different scenarios makes things unclear and less applicable across the U.S. Additionally, when labs measure different information to use in a particular soil health scoring system, it is not easy for a producer to know what they are lacking or what is changing. Assigning weight to certain metrics for improvements in certain factors can create bias that is good for some soil series and climatic conditions but not for all.

Conventional agricultural management, including intensive tillage, few crop rotations, and no cover crops, can negatively affect soil health metrics (Devine et al., 2021). In contrast, adopting reduced-tillage or no-tillage management and crop rotation can improve soil health indicators (Chahal et al., 2021). Cover crops can also improve soil health indicators such as bulk density, soil strength, water use efficiency, and mineralizable C and N (Andrews et al., 2018; Chalise et al., 2019; Sanders et al., 2018; Wade et al., 2018). Improvements that are desired by producers from increased function are overlapping with soil health indicators. Soil health and cover crops are becoming terms that get used together but management techniques with them are key to that being true. In agronomic production, soil loss, soil function including nutrients and water along with weed management are all concerns. The balance between the production of the cash crop and use of conservation techniques to build soil health is key to achieve optimal yield and improved soil health.

Cover Crops and Soil Health

Cover cropping has generally been applied in row crop agriculture for various reasons. One interest is keeping the ground covered and using living plants with roots to do so can provide positive effects on weed demography as a weed management strategy (Weisberger et al., 2024). The ground covered by annual cover crops in the non-cash cropping season reduces soil erosion (De Baets et al., 2011). While erosion can have negative effects on specific areas, cover crops can help retain the soil in place, but winter temperatures that cause plants to die make the below-ground root structure key for the desired effects of stable soil structure (De Baets et al., 2011). These cover crop roots can reduce the amount of nitrate leaching out of the root zone (Isse et al., 1999). Annual and perennial cover crops have purposes beyond basic soil health including reducing weed pressure and nutrient leaching (Isse et al., 1999; Weisberger et al., 2024).

Common annual cover crops that are used in the southeastern United States when ground cover or other benefits are desired are cereal rye (*Secale cereal*), forage radish (*Raphanus sativus* L.), and crimson clover (*Trifolium incarnata*), used outside the cash cropping season (Decker et al., 2022). The use of annual cover crops provides a limited window when the cover crops improve soil health parameters. Planting annual cover crops earlier in the season is one way to extend the time of action the cover crops can work, but the later termination date of cover crops is the factor with statistically greater below-ground biomass (Ruis et al., 2020). Having later termination of cover crops increases root biomass, which is beneficial, indicating that the more work time, the greater the benefits. Strategizing a way to get improvements from cover crops with the use of multicover crop species mix that are carefully selected to benefit the services from cover crops that are not just more biomass production effects (Finney et al., 2016). Even the use of interseeded cover crop growth with a non-leguminous cover crop like poaceae has been explored to start growing in the summer. Still, the climactic conditions in some states like Kentucky are too warm in the summers for plant survival (Stanton et al., 2020). While the greater amount of time from annual cover crops is desired, perennial cover crops have the ability to work year-round with continual improvements to the soil health indictors.

A few perennial cover crops can be used due to the cash crop's climatic conditions required and production practices. Early reports of living mulches used with clover successfully used a 30-cm drill band to plant crops into (Hartwig & Ammon, 2002). Other observations from their study are that soil moisture is not as much of an issue in orchards with greater precipitation. The use of living mulch in corn can have challenges in competing for soil moisture near the surface until the corn's rooting system develops to get lower in soil profile moisture. Their last main observation is that competition for nutrients was not as key, and N was provided with the leguminous cover crop (Hartwig & Ammon, 2002). In Georgia, living mulches focused explicitly on using Durana clover (*Trifolium repens* var. 'Durana') as the perennial cover crop. Other types of clover have different requirements that allow them to be useful in other systems. One example is Kura clover living mulch, which has been applied in areas like Minnesota with different agronomic production practices and climatic regions compared to the Southeastern U.S. (Turner et al., 2016). Other applications of living mulch outside of Georgia in the Southeast include applications in Tennessee that incorporate grazing (Quinby et al., 2023a; Quinby et al., 2023b).

Durana clover has been established as a known functioning system in corn with the added benefit of providing N (Andrews et al., 2018). Soil moisture is another factor noted to be important for maintaining clover for regrowth. At the same time, temperatures have to stay above a certain temperature to prevent severe injury or death of the clover in the winter. Greater water requirements are required to maintain an ideal volumetric water content for cash crop production. Water use efficiency increases with cover crop use, but the benefit is not observed in clover as "living mulch" (LM), likely due to two plants growing simultaneously (Sanders et al., 2018). Compared to annual cover crops, the LM system has shown faster and greater improvements in soil health (Hill et al., 2021). The increase of soil organic matter and the importance of C in the soil highlight the importance of cover cropping with the greater advantage of using a perennial system (Hill et al., 2021). Biological improvements in the soil from utilizing the living mulch system include benefits in the soil bacterial community compared to other commonly used cover crops (Li et al., 2023).

Selection of Durana clover is released through the selection from the three primary growth habits of clover. Due to the shading of clover from canopy closure of the cash crop, the selection of a clover variety that is resilient to grazing will have a similar response for successful regrowth after the summer is the rational. In Georgia, the development of the Durana variety, which has a long flowering period with prolific seeding and stolon, creates an aggressive regrowth ability (Andrae, 2009). Sufficient canopy closure of a corn cash crop in Georgia occurs approximately 40 days after planting resulting in clover dying back followed by decomposition and then nutrient release (Sanders et al., 2017).

Selection of a cover crop to change soil properties is another management decision in production practices that can improve the land for optimizing cash crop production. Producers are concerned about improved soil structure and bulk density each spring when planting is going to occur. Then, after the seeds are planted, the water moves into the soil and stays in the rooting zone. All of these factors are affected by management choices. For example, improvements in soil chemical properties like soil organic matter can lead to improvements in physical and hydraulic properties. Utilizing cover crops in a field can build soil C, and another effect when C is increased in the field is lower bulk density and increased saturated hydraulic conductivity (Hubbard et al., 2013). These increases in C are likely changing the structure of the soil, as evidenced by lower bulk density and increased saturated hydraulic conductivity.

The effect of cover crops below the soil surface is also tied to covering the ground and protecting the soil from rainfall or erosion as armor for the benefits of aggregate formation. When breaking down the aggregates from uncovered soil, the rainfall can create an impermeable layer often called a crust. Having a crust on the soil can reduce infiltration, but using cover crops can cause infiltration rates and water-holding capacity to improve (Chalise et al., 2019; Rankoth et al., 2021). The increased water-holding capacity in the soil is connected to the addition of organic matter in the soil from long-term cover crops (Rankoth et al., 2021). The building of organic matter leads to the building of soil aggregates that change aspects of soil structure by adding pore space which lowers bulk density (Chalise et al., 2019).

Changes in soil structure can reduce penetration resistance as evidenced by 65% of studies in a meta-analysis from Blanco-Canqui & Ruis (2020). These reductions were also observed with one-third of the studies having changes in bulk density and 52% having increased water-stable aggregates. The reduction of penetration from the use of plants is known as biological tillage. Having a tap root cover crop as forage radish has a better reduction in penetration over rye which has a fibrous root system (Chen & Weil, 2010). These results occurred from the fibrous roots having difficulty going through compacted soils with few root channels and high clay content. Variable results were found in the southeastern United States for changes in penetration resistance from cover crops in short-term experiments (Decker et al., 2022). Issues of high clay and soil organic C can cause aggregates to be highly stable preventing the additions of more organic C from cover crops from changing the amount of water-stable aggregates (Decker et al., 2022; Steele et al., 2012). Cecil soil series has been noted for the Bt1 soil horizon controls on the water flow when the soil surface is not crusted, commonly occurring on the bare ground in Piedmont soils (Radcliffe et al., 1990). Cover crop impacts are primarily near the soil surface. For example, Ardenti et al. (2023) found changes in C and aggregate stability in the 0-5 and 5-15 cm soil layers as the layers effected by cover crop, but not in the 15-30 cm layer (Ardenti et al., 2023). Cover crops could introduce some variability within the fields by exacerbating fertility or moisture issues through varying levels of biomass production.

Cover crops can affect inherent properties, which are a key determining factor for saturated hydraulic conductivity. Because of in-field variability from tractor movement and other field activities, the addition of pedogenic spatial variability may be useful to identify in-field spatial variability in saturated hydraulic conductivity (Bodner et al., 2013). Multiple measurements are needed in the various results of cover crops and infield variability effect, resulting in various reports on changes from cover crops' overall effect (Bodner et al., 2013; Carof et al., 2007; Hubbard et al., 2013). Different cover crops having different rooting structures causing penetration patterns into the soil is often thought to be connected with penetration resistance (Chen & Weil, 2010). Hydraulic conductivity on silt loam soil had no major rate changes between tap root structure and fibrous roots (Carof et al., 2007). Increasing hydraulic conductivity from cover crops increases water flow into the soil and reduces runoff, especially under intense precipitation events (Yu et al., 2016).

Coastal Plain soils often have sandy textures with lower aggregate stability than soils in other areas, but using cover crops can significantly increase the formation of aggregates (McVay et al., 1989). The greater percent of aggregates also had greater water infiltration from the effect of cover crops, which indicates improved soil structure (McVay et al., 1989). Improvement in pore space and distribution is an effect that cover crops can change, which is indicated through greater plant available water with the specific improvement of wilting point (Villamil et al., 2006). Carbon added to the soil is a factor that is linked to other factors for change, and greater sequestration of C is linked to greater biomass independent of annual cover crop type (Ardenti et al., 2023). These properties are all noted as taking a long time for changes to occur in the use of annual cover crops and are often thought to need to be optimized for a maximum amount of time for changes (Blanco-Canqui et al., 2023). Planting into still-living annual cover crops at cash crop planting is one strategy to get more time for the desired cover crop effect (Nunes et al., 2023). The utilization of perennial cover crops when factors allow in the field to capitalize on the element of time of cover crop presence throughout the year creates a better opportunity for change.

There are concerns in Georgia, such as N leaching from the cash crop rooting zone from high precipitation in a humid subtropical climate. One way to mitigate this is with the use of cover crops, including black oats or oilseed radish as a nutrient retention that will be terminated before cash crop planting (Schomberg et al., 2006). These cover crops provide the benefit of not immobilizing the N like some cover crops like cereal rye which alters the C to N ratio, allowing for fertilization methods to follow standard practices. The additional benefit beyond nutrient dynamics was keeping the ground covered in a large amount of biomass to help prevent soil erosion (Schomberg et al., 2006). Reduction in soil erosion allows soil to stay in place, creating a stable area with aggregates and making changes in soil surface texture less likely.

Cover Crops for Nutrient Dynamics

Perennial cover crops, known as a ‘living mulch’ system, can potentially improve many aspects of crop production (Andrews et al., 2018; Sanders et al., 2017). Improved soil quality from cover crops has increased cotton yields in the southeastern United States (Nouri et al., 2019). Production benefits from a living mulch have been explored for C and N in similar cropping systems but lack focus on other vital macro-nutrients and micro-nutrients (Andrews et al., 2018; Ginakes et al., 2020; Sanders et al., 2017). Plant nutrients such as phosphorus (P), potassium (K), calcium, magnesium, zinc, and manganese have crucial roles in plant growth and physiological functions that vary throughout the growing season. The use of a LM can maintain and release nutrients back into the system during the season. Perennial grass cover crops have also been used for nutrient retention, increased soil C retention, and improved potential mineralizable N (Banik et al., 2020).

As cotton develops, the canopy shades out the living mulch, resulting in death and decomposition, releasing nutrients. Potassium as an example is a very mobile nutrient that can be taken up in excess when large amounts are available in the system (Bartholomew & Janssen, 1929). A living mulch system managed differently by mowing was noted for taking up large amounts of K and then holding it in the system before being released as a response to fresh cover crop growth (Deguchi et al., 2010). While perennial cover cropping can hold nutrients if managed by mowing, resulting in an active high amount of biomass growth when the cash crop is growing, causing issues in the nutrient supply in the system in terms of availability to cash crop when needed (Deguchi et al., 2010). The positive side of using an LM system is that it can take up excess nutrients to prevent loss from the system, but knowing the growth of your perennial system and how it responds to management can affect nutrient dynamics. The released nutrients are taken up at critical times when they are needed most by cotton for growth and boll development, which can significantly impact yield and quality. The time of critical need in cotton occurs during reproductive growth with more than half of the amount of the nutrients listed previously taken up during reproductive growth (Rochester et al., 2012).

Pedotransfer Functions to Predict Soil Health Metrics

Hard-to-measure properties like water retention for plant available water content (AWC) and infiltration rate are important to soil health and useful for producers (Bagnall et al., 2022b). Available water content is the water retained between wilting point and field capacity. Field capacity is the greatest amount of water a field can hold after a saturated soil has drained for 24 h (0.033 MPa; Schaap et al., 2001; van Genuchten, 1980). Wilting point is considered to be the minimal amount of water in the soil that plants can still utilize (1.5 MPa; van Genuchten, 1980). This is because the potential forces of plants can only be so strong that they outdo the potential of soil to hold the water. Field saturation, field capacity, and wilting point are all important points along the soil water retention curve (SWRC), but the measurement can be time-consuming and costly.

Knowing the key points on the soil water retention curve (SWRC) can help plan irrigation strategies. The selection of points that are of interest in SWRC to producers includes field capacity and wilting point making plant available water. The technique of estimating hard to measure soil properties from soil physical and chemical properties that are easier to measure is called pedotransfer function (PTF; Patil & Singh, 2016). Producers can use the information to estimate these factors to make management choices (Bagnall et al., 2022a). Cover crops can be used to increase water use efficiency for a variety of crops and locations and can be especially important for all locations including Georgia soils (Sanders et al., 2018). Using a perennial cover crop of LM creates a need for greater soil moisture from two plants growing in the field simultaneously.

Measuring soil hydraulic properties is more complex than the relatively easier-to-collect soil physical properties for the use of PTFs. Measurement of soil physical properties like texture and bulk density often requires less specialized equipment and is generally cheaper to obtain than hydraulic properties. Common measurements used in PTFs include soil texture, bulk density, aggregate stability, and soil strength. The van Genuchten (1980) prediction equation works with limited soil texture and water content information. Expanding on this model is the Rosetta model that can be used to add information on particle size and bulk density are added in to refine the model that makes it more specific to the site-specific location (An et al., 2021). Rosetta has been updated in ways it predicts by changing the weights of the parameters in Rosetta3 from the earlier model used in Rosetta1 (Schaap et al., 2001; Zhang & Schaap, 2017). Another common model used that adds more information from the addition of C as a coefficient to improve predictions is Saxton and Rawls (2006). Other papers have used organic matter or C from the soil in some form to make predictor functions (Bagnall et al., 2022b; Nemes et al., 2003; Patil & Singh, 2016).

Having plant AWC is of interest to producers and having more site-specific models to improve predictions aids in reducing erroneous interpretations. Also, more single-point samples are needed to cover an area that are labor- and time-intensive to measure for hydraulic properties. The use of composite samples of physical soil data can help predict hydraulic properties and improve the practicality for covering larger areas. Finding the key factors that affect the SWRC, like texture, due to surface area, and other way to change the capacity by altering surface are for retention is through the increase in soil organic matter. Increases in soil organic matter can come from increases in plant residue and incorporation and not removal from the system through practices like cover crops. Organic matter has a natural attraction of water, which can build the overall water-holding capacity. When building a model, adding the information of texture and organic matter or C content to be used in the pedotransfer function as these properties have connections to management changes affecting the predicted points on the SWRC. The two points of interest along the SWRC can be measured using single-point measurements at field capacity using Tempe cells (SoilMoisture Equipment Corp., Santa Barbara, CA) or pressure plates and the wilting point measured by WP4C (Meter Group, Inc. USA) or pressure plates. Replacing these two methods with simpler measurements of texture, organic matter, and other physical properties can save time and cost.

Summary

Annual cover crops are commonly grown in rotation with standard cash crops such as corn and cotton to improve soil quality, reduce erosion, and retain nutrients. The overarching research focus of my dissertation is to evaluate the benefits of using a white clover (*Trifolium repens* var. 'Durana') 'living mulch' as a perennial cover crop for soil quality and crop production in several cropping systems in Georgia. A suite of chemical, physical, and hydraulic soil properties were used to evaluate the effects of the white clover living mulch system. These properties were observed for changes in three agricultural systems common in Georgia, including corn (*Z. Mays*), cotton (*Gossypium L.*), and pecans (*C. Illinoinensis*). Additional use of taking measured physical parameters to predict hydraulic properties using modeling from collected data used in soil health evaluation gets more function out of the data for additional applications. The common thread of this paper is soil health, which improves soil function and quality by measuring, interpreting, and predicting soil properties. It also leads to greater use and understanding of impacts on soil health, especially from cover crop use.

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CHAPTER 2

A FOUR-YEAR COMPARISON OF PERENNIAL AND ANNUAL COVER CROP IMPACTS ON SOIL HEALTH INDICATORS

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Abstract

Soil health indicators are soil properties that are sensitive to changes in management and important for soil function. One management strategy often used to improve soil health is the use of cover crops. Annual cover crops are common in row crop systems of the United States, whereas perennial cover crops are often used in other systems such as orchards. This four-year study (2019-2023) compared the impact of different cover crops on soil physical, chemical, and hydraulic parameters in the upper 30 cm of a soil under continuous no-till cotton (*Gossypium hirsutum* L.) management in the Georgia Piedmont. Treatments included three cover crop systems (cereal rye (*Secale cereale*), crimson clover (*Trifolium incarnatum*), and perennial white clover (*Trifolium repens* var. 'Durana') living mulch (LM) and bare ground. Cover crop treatment significantly affected bulk density, soil moisture at field capacity, and porosity. In 2021, LM had 2.4 mg kg^{-1} greater potentially mineralizable nitrogen (N) at the 0-5 cm depth than the bare ground control. Potassium (K) had a significant buildup in the LM to year three from 106 to 160 mg kg^{-1} before decreasing in year four to 106 mg kg^{-1} likely related to previous year nutritional needs and application changes affecting the data. Cover cropping promotes many soil health principles, though changes in the soil indicators are not always quick to respond to management.

Keywords: Living Mulch (LM), Mineralizable Nitrogen, Soil Health Indicators, Cover Crops

Introduction

Cover crops are used with many cash crops like corn and cotton because they protect soil from erosion, capture unused mobile nutrients, improve soil biology with bacterial community changes, and improve soil-water relationships for crop production (Adler et al., 2020; Chalise et al., 2019; De Baets et al., 2011; Li et al., 2023; Rankoth et al., 2021). As such, cover crops play an important role in addressing soil health principles outlined by the USDA-NRCS because they provide a soil armor against erosion, evaporation, and temperature extremes, maintain a living plant root in the soil, and contribute to plant diversity (USDA, 2021). Soil health generally represents the ability of a soil to function, and the soil properties used to monitor it are considered to be dynamic because they are sensitive to management practices over the course of decadal time scales (Doran & Parkin, 1994). Two common practices for improving soil health are reduced tillage and the use of cover crops (Acuña & Villamil, 2014; Algayer et al., 2014; Chahal et al., 2021; Chalise et al., 2019; Liu et al., 2005). Although both annual and perennial cover crops can improve soil health metrics such as aggregate stability, hydraulic function, bulk density, and organic carbon (C) (Acuña & Villamil, 2014; Chalise et al., 2019; Gallardo-Carrera et al., 2007; Liu et al., 2005; Rankoth et al., 2021), the overwhelming majority of work has been focused on annual species.

Of the more than 1.6 million hectares cropped in Georgia during 2017, only 12% incorporated cover crops, with the most common cover crops being annual species like cereal rye and crimson clover (NASS, 2017). A smaller fraction of cover crops are perennial species, such as white clover (*Trifolium repens*), which are becoming more common (Alexander et al., 2019; Andrews et al., 2018; Hartwig & Ammon, 2002; Hill et al., 2021; Ochsner et al., 2010; Pearson et al., 2014; Quinby et al., 2023; Sanders et al., 2017; Turner et al., 2016). The selection of perennial species for LMs is often dictated by the regional climate and other agronomic practices (Hartwig & Ammon, 2002). Previous research has indicated that sufficient time is needed to see measurable soil health benefits from using cover crops. For example, Hill et al. (2021) found that a white clover LM expedited soil health regeneration in a corn production system compared to annual cover crops after three years, but some work with annual cover crops suggests it may take six years or more for changes in soil health properties (Basche et al., 2016; Blanco-Canqui et al., 2023;). Annual cover crops have a limited window of time to impact soil health because they only grow during part of the year. Conversely, perennial cover crops grow year-round, potentially influencing soil for more time during the year.

A wide variety of soil chemical, physical, and biological properties have been suggested as soil health indices. For example, aggregate stability, bulk density, saturated hydraulic conductivity, water retention, soil organic C, soil mineralizable C, cone penetration resistance, and others have been used to quantify soil health (Bagnall et al., 2023; Hubbard et al., 2013; Liu et al., 2005; Nouri et al., 2019; Steele et al., 2012). Some commonly-measured soil health indicators exert positive feedback on one another, which can compound improvements for soil properties over time (Nouri et al., 2019). For example, increases in soil C have been correlated with more water-stable aggregates (Liu et al., 2005; Steele et al., 2012) and lower bulk densities (Hubbard et al., 2013). To help address the overlap of some of these properties, several approaches have been suggested to recommend a minimum dataset for aggregation to determine the main indicators of soil health (Bagnall et al., 2023; Norris et al., 2020). Selecting indicators that are sensitive to management practices for a given suite of soils is critical for determining ways to quantify changes in soil health, especially in agronomic production systems.

Changes in soil physical properties have many interrelated effects that can be altered through the use of cover crops. For example, the use of cover crops to create changes like improvement in soil structure from C inputs and reduced tillage has also been shown to increase saturated hydraulic conductivity (Hubbard et al., 2013). Water-stable aggregates, bulk density, and saturated hydraulic conductivity are often influenced by soil structure or contribute to it, as is the case for aggregation. A large effect on properties measured from wheel tracks shows how wheel rows reduce the beneficial effects of cover crops. The differences have a greater impact over time from cover crops when an active annual compaction from planting and harvest are not occurring (Hubbard et al., 2013). Keeping the soil surface covered with cover crops works as an armor to the soil that physically protects it and adds C which acts as an organic glue. The physical protection comes from the soil aggregates being covered and shielded from rainfall and erosion forces that can cause a breakdown on an aggregate scale. Changes in soil structure in agriculture fields have been noted after as little as one year of using cover crops (Acuña & Villamil, 2014), but adequate time is often needed to realize benefits. Besides breaking down aggregates, rainfall can also create a physical crust on the soil surface, especially on bare soil. This crust can reduce the water infiltration rates though cover crops can help offset this problem by increasing water infiltration, water held in soil (Chalise et al., 2019; Hubbard et al., 2013), and the amount of subsurface water recharge and soil moisture (Rankoth et al., 2021). Building of aggregates changes pore space, leading to effects on bulk density that cover crops can reduce while still having improved soil structure (Chalise et al., 2019).

Most of the work on LM systems in the southeastern US has been done in corn production systems (Andrews et al., 2018; Hill et al., 2021; Quinby et al., 2023; Sanders et al., 2018; Sanders et al., 2017). The desire to move this to other cash cropping systems is likely due to the potential for improving soil health and providing inputs of N for the cash crop along with other agronomic factors (Andrews et al., 2018; Hill et al., 2021; Weisberger et al., 2024). For example, this system has recently been evaluated as a weed management tool for cotton production in Georgia (Weisberger et al., 2024). Expansion of the LM into systems other than corn requires a better understanding of challenges and benefits before recommending it for large-scale production. For example, there is a significant knowledge gap in our understanding of how a perennial white clover LM impacts soil health in cotton production systems of the southeastern US.

The overarching goal of this study was to quantify changes in soil health parameters in a no-till cotton production system with common annual cover crops, a perennial cover crop, and a bare ground control over four growing seasons. More specifically, we aimed to identify the soil properties most sensitive to cover crop treatments to identify dynamic soil health indicators in our study area. We hypothesized that the use of cover crops would cause changes in some soil health parameters throughout the four-year study. Another hypothesis was that LM would increase N mineralization rates and soil C as a result of the continually growing leguminous cover crop.

Materials and Methods

Experimental Design and Site Information

The study was established in the fall of 2019 and continued through the 2023 cropping season at the John Phil Campbell Research and Education Center near Watkinsville, GA (33°52′09.5″ N 83°26'59.8″ W; 219 m elevation) in an area where the previous crop was no-till cotton with no cover crop. The experimental design was a randomized complete block with four treatments and four replicates. Each of the 16 plots were approximately 10.9 x 16.5 m (to accommodate 12 rows of cotton). Treatments included a perennial cover crop of 'Durana' white clover (*Trifolium repens*, Bouton et al., 2005) referred to as a living mulch (LM), two annual cover crops, crimson clover (CC, *Trifolium incarnata*) and cereal rye (CR, *Secale cereal*), and bare ground with no cover crop (CO). The CR and CC cover crops were terminated by the combination of glyphosate applied at a rate of 2.52 kg ae ha^{-1} after being roller crimped approximately two weeks before cotton planting. LM strip width was established using banding nozzles on a tractor-mounted drop sprayer with Glyphosate herbicide (1.26 kg ae/ha) and dicamba herbicides (0.81 kg ae/ha) applied at 280 L/ha. All treatments used no-till management for cotton with a yield goal of 840 kg ha^{-1} and an associated N requirement of 67 kg ha^{-1}. Nitrogen credits provided by CC and CR treatments were determined according to the Cover Crop Nitrogen Availability Calculator (Gaskin et al., 2020, available at https://aesl.ces.uga.edu/mineralization/), and the remaining N required was supplied with urea-ammonium nitrate solution (UAN). The LM plots did not receive any N fertilizer in any year of the study. Irrigation inputs were based on UGA extension guidelines to reach the total needed for the week when precipitation didn’t meet that need (Hand et al., 2023). The same trial location was used to explore the influence of these treatments on weed management dynamics and is further described in (Weisberger et al., 2024). The soil is mapped as a moderately eroded Cecil sandy loam (fine, kaolinitic, thermic typic Kanhapludults) with a 2 – 6 % slope (Soil Survey Staff, 2019).

Sampling and Measurements

Soil push probe cores (n = 15) were collected in April to May each year (prior to cotton planting) and composited by plot to represent 0-5, 5-15, and 15-30 cm depths. Composite samples were air-dried and sieved through a 2-mm sieve for subsequent analysis. Mehlich 1 extractable nutrients (P, K, Ca, Mg, Zn, and Mn) and soil pH were determined following (Kissel & Sonon, 2008). Water pH was approximated from a calcium chloride pH following Kissel and Sonon (2008). For aggregate stability, 4 grams of each air-dried soil were pre-wetted using a humidifier before using an Eijkelkamp wet-sieving apparatus (Kemper & Rosenau, 1986). Soil texture was measured using a Beckman Coulter Laser particle size analyzer (Beckman Coulter LS 13 320, Indianapolis, IN). All non-push probe soil samples were taken after cotton planting in either May or June each year for other soil physical and hydraulic properties. Bulk density measurements were taken with one from each plot using a 6-cm ring with a diameter of 8.1 cm at the surface (0-6 cm), upper root zone (9-15 cm), and lower depth (19-25 cm) to represent the 0-5, 5-15, and 15-30 cm depths (Blake, 1965). Twenty-gram subsamples from air-dried bulk density samples were subset to get oven-dry weight to get the total oven-dry equivalent of the whole sample. Separate undisturbed soil cores were collected from the same sample depths as the bulk density to determine water content at field capacity (0.033 MPa; FC) using Tempe cell ring system (SoilMoisture Equipment Corp., Santa Barbara, CA) and the wilting point (1.5 MPa; WP). After measuring FC, the air-dried soil from the ring was used to determine the water content at the wilting point using a WP4C (Meter Group, Inc. USA). Plant available water content (AWC) was calculated as the difference between FC and WP. Soil strength was measured at 9 points in each plot using a Rimik CP40II digital cone penetrometer (Cinstral Exports, Toowoomba, Queensland, Australia) averaged by depth in 2.5-cm depth increments. Soil hydraulic conductivity (K_{sat}) was measured at the soil surface using a SATURO dual-head system (METER Group, Inc. USA) with one replication per experimental unit.

Total organic C (TOC) and total organic N (TON) were determined by dry combustion using air-dried composite samples that were ball-milled (Bremner, 1996). Potentially mineralizable C and N were determined from field-moist soil samples taken from 0–5 and 5–15 cm depths of all plots in 2021 and 2022. Samples were refrigerated at ~4.5 °C until the commencement of incubation which occurred within three days of sampling. Samples were sieved through 2 mm to remove roots and large debris. Duplicate ~12 g samples at field moisture were placed in 1-L jars containing 20 ml of 1M sodium hydroxide as a CO_2 trap and extra water to cover the base of jar was done to maintain soil moisture. The jars were aerated halfway through the incubation time. Mineralizable N was measured after a 30-day incubation at 26 °C as the method outlined in Wood et al. (1992). Before and after incubation, the soils were analyzed for mineral forms of N (NH_4-N and NO_3-N) that were extracted using 1M KCl (ratio of 5 g of soil to 20 ml of KCl). A subsample of field-moist soil from each sampled location was used to represent pre-incubation samples and the soil used in the incubation was extracted following incubation. The potentially mineralizable N was determined as the difference in NH_4-N and NO_3-N before and after incubation. Evolved carbon was quantified using a Shimadzu TOC-5000 (Shimadzu Scientific Instruments, Inc.) to quantify the total inorganic C in a subsample of the CO_2 trap.

Statistical Analyses

Differences in soil properties were compared using ANOVA and pairwise t test that was performed in R studio version 2023.12.0 using R version 4.3.2 with rstatix, dplyr, ggplot2, and tidyverse packages (Kassambara, 2023; R Core Team, 2021; Wickham H, 2016; Wickham H et al., 2019; Wickham H et al., 2023). The pairwise t test allowed for paired and unpaired analysis for repeated measure analysis of the samples as they sampled from the same locations over time. Tests for outliers, normality, and homogeneity of variance was performed prior to analysis and utilized to perform next steps of the data analysis if adjustments were needed. The depth, treatment, and year was analyzed in a three-way ANOVA. Additional ANOVAs were conducted by depth for two-way interaction from treatment and year was analyzed, and only the main effects were presented when there were no significant interactions. Mineralizable N data had lab replicates that were averaged prior to statistical analysis. All analysis was done using an α level of 0.1.

Results and Discussion

Soil Physical and Hydraulic Properties

No significant three-way model occurred for any measured property (water stable aggregates (WSA), available water content (AWC), field capacity (FC), wilting point (WP), and porosity (Not shown) but FC had treatment and depth interaction (Table 2.1). Bulk density (BD) was significantly affected by treatment, depth, and year as main effects, but year and treatment and year and depth had significant interactions with all three depths included in the analysis (Table 2.1). In the main effect of depth in ANOVA being important and likely a connection to clay increases by depth. From the texture analysis from a mean combined from all composite sampled analyzed for texture by depth had a texture class change by depth. The 0-5 cm was loam, 5-15 cm clay loam, and 15-30 cm clay with an overall clay content increase of 26% from 0-5 to 15-30 cm. No depth interaction with any other main effects for all of the soil physical and hydraulic properties that had a depth component caused the focus on the upper sampling depth zone from 0 to 5/6 cm. This zone is also where the cover crop roots were readily present in the area with the greatest probability of impact from the treatments of different cover crops and over time.

In this four-year study, bulk density was not significantly affected by cover crop treatments and time interactions for all depths analyzed by depth. Surface bulk density did not change significantly across the four years of measurement within treatments (Figure 2.1). The cereal rye (CR) treatment statistically had the greatest bulk density compared to bare ground (CO) and living mulch (LM) compared to treatments without year separation. This may reflect possible compaction caused by the roller-crimper as part of cover crop termination a few weeks prior to sampling. The compaction did not increase over time for the treatments with roller crimper of CC and CR, showing it did not have an additive effect. Roller-crimpers are a weighted metal roller applying pressure to terminate the cover crop when pressed on the soil surface. In Alabama, also in the southeastern USA physiographic region, there were increases in compaction from roller but there were no increases with additional roller applications in not droughty years (Kornecki et al., 2013). Sample timing prior to cover crop termination would likely have less effect on bulk density as cover crop had time to work without a major compaction event. Other field activities that could have caused compaction are drill planter operations in the fall for cover crops and other wheel traffic associated with cotton production (herbicide, growth regulator, harvest, etc.).

Similar to bulk density, the two-way models for porosity were not significant. When analyzed at a depth of 0-6 cm, porosity was not significantly different by treatment across time for the interaction, but within-year differences occurred (Table 2.2). Statistically, the LM had the greatest porosity and lowest bulk density compared to CR in terms of the main effect of the treatment. Porosity had minimal fluctuations in the ranges of values between treatments with generally greater porosity in 2021 and less in 2022 (Table 2.2). The minimal treatment effect on both bulk density and porosity may be a result of the macro pores present in the soil resulting in the cover crops using the same preferential root channels each year, preventing changes over time (Lucas et al., 2019). Compaction measured with bulk density and porosity results are connected to AWC, which had a range in the treatment means of 8% and 17% for the 0-6 cm depth, and had no statistical separation between treatments across four years (Table 2.2). There were no significant two-way interactions for AWC, FC, or WP when factoring in depth, treatment, and year. Similarly, there were no treatment or year differences for FC or AWC for the 0-6 cm samples. The WP was significantly different by treatment when the 0-6 cm samples were analyzed independently and for all years and showed the LM had a statistically lower WP than CC and CR at the surface.

Another measurement associated with compaction and disturbance is aggregate stability. When considering all depths, WSA was significantly different by year and depth (Table 2.1). The surface 0-5 cm had 3% greater WSA than the 5-15 cm depth and 2022 and 2023 was greater than 2021 but not different for 2020 with any years. Comparing the aggregates in the 0-5 cm depth resulted in a lack of statistical differences by treatment or time, however there was a numerical increase in WSA for LM and CR over time. Detection of statistical differences were likely limited due to low variation in measured values for all treatments with a range of less than 10% after 3 points were removed but were not indicated as extreme outliers, with the points not removed the range was 21.7 (Table 2.2). While some numerical trends occurred after four years, our results agree with those reported by Blanco-Canqui et al. (2023) who found no differences in aggregate stability after four years of cereal rye cover crop on silt loam soils in Nebraska. They did find significant differences in soil properties including WSA after eight years of a cereal rye cover crop, and suggested low biomass input for the first four years may have explained the lack of an effect after four years (Blanco-Canqui et al., 2023).

Saturated hydraulic conductivity (K_{sat}) measured at the soil surface had a significant interaction in the main effects and was significantly different by both year and treatment as the main effect (Table 2.1). Aggregated across years, the K_{sat} of LM was 15.9 cm hr^{-1}, which was statistically greater than other treatments (9.61, 8.73, and 6.97 cm hr^{-1} for CC, CO, and CR, respectively). The most notable difference in K_{sat} was in 2021, when the LM treatment showed a significant increase relative to other treatments and remained numerically greater after that (Table 2.2). The lower compaction found in the LM treatment can explain the greater $K_{sat,}$ as both variables are affected by soil surface conditions. In Missouri, on silt loam soils, it was found that significant improvements over the previous years occurred after five years for K_{sat} (Çerçioğlu et al., 2019). Another study in Missouri found that K_{sat} improves from increases in macro pores, and cover crops are one way to achieve this (Haruna et al., 2018). Haruna et al. (2018) found that cover crops create a lasting impact on K_{sat} whereas tillage effects, while initially faster, don't last over time.

Soil strength was difficult to interpret in this study because it is influenced by soil moisture. Some studies have attempted to correct soil strength for soil moisture, but there is not a clear recommendation for how to do this (Chalise et al., 2019; Decker et al., 2022). Here, we focus on the cumulative effects of management on soil strength by only showing the measurements that followed four years of management (Figure 2.2). Overall, the pattern for soil strength was similar across treatments and showed increases to approximately 20 cm depth, then decreased from 30-40 cm (Figure 2.2). After four years, the measurements by depth had some separation that indicated the LM had the greatest compaction between 20-35 cm from soil surface, whereas other treatments were more similar. Soil moisture calculated from water retention cores taken at 9-15 and 19-25 cm showed that LM had significantly less soil moisture than other treatments (α=0.1). In some cases, the influence of soil moisture condition can supersede that of management. For example, another study in the southeastern USA located on a

Hartsells fine sandy loam soil in Alabama had applications of different types and amount of times roller-crimper pressed on the cover crop and showed that drought in one year created increased soil strength compared to cover crop rolled, which helped with an increased soil moisture in that location (Kornecki et al., 2013). The connection between greater above ground biomass and decreases in soil strength has been demonstrated in the southeastern USA which could have subsequent impacts on soil moisture, further complicating interpretations of soil strength measurements as more biomass production increases soil moisture requirements (Decker et al., 2022).

Soil Chemical Properties

The three-way interactions of main effects were not significant for TOC or TON, and the two-way interactions between the main all the effects were not significant in the full model (Table 2.3). Depth was significant for both TOC and TON with greater concentrations in the 0-5 cm depth compared to other depths. Additionally, treatment and year effects were significant for TON. The significance of depth in both TOC and TON followed the same pattern as measured soil physical and hydraulic data. This is not surprising given that the surface receives the most disturbance and application all nutrients were surface applied. The nitrogen applications varied by cover crop treatment with respect to N credits gained from the cover crop to reach the cash crop needs (Weisberger et al., 2024). The zone of impact discussed for soil chemical properties from this point on was based on the combination of factors, including the zone of likely impact from direct root impact of cover crops to assess differences across time in the system. The importance of C as a common indicator in soil health and fertility is well established partly resulting from the suspected effect of soil C in creating a reservoir of soil nutrients (Franzluebbers et al., 2000).

The TOC in 2021 and 2023 was numerically greater for LM at the 0-5 cm depth and 2022 was only lower than cereal rye (Table 2.4). The trend for increases in total C at 0-5 cm depth for LM in this study was similar to results of Franzluebbers et al. (2000) who reported increased total C in pastures compared to tilled row-crop fields in the same Piedmont physiographic region. Though a direct comparison cannot be made between their study and ours, the LM is used to cover the ground and not tilled similar to pasture for some strips in the field which creates some parallels to their study. The numeric effect on C and the numeric increase in WSA in the LM treatment showed a trend that matched the statistical changes for increased C and WSA found on soils in Nebraska when switched to no-till conservation agriculture practices (Blanco-Canqui et al., 2022). Increases in soil C using annual cover crops in cotton production systems has been associated with increases in water infiltration and reductions in penetration resistance (Delaune et al., 2019). The TON was numerically greater for LM in 2021, 2022, and 2023, but had little separation from other treatments. Potentially mineralizable N was statistically greater in LM than bare ground (CO) for the 0-5 cm depth in 2021 and numerically greater than all other treatments in both years (Table 2.5). This is especially important because the LM treatment received no N fertilizer in any year whereas the CO treatment received 67 kg ha^{-1} of UAN annually.

The soil pH had no significant three-way and no significant overall two-way interactions when depth was included in the model (Table 2.3). The focus on soil pH in the 0-5 cm depth had a range of 1.1 units across all of the data from four years, ranging from 5.9 to 7.0, with a mean of 6.4 (Table 2.4). There were no significant differences between treatments over time additionally as anticipated with no lime being applied to the study to cause impacts. The limited range of pH values by year and treatment reflects the intensive management of the site that included the uniform addition of lime to the field when needed prior to the first cash cropping year (Kissel & Sonon, 2008).

Potassium had a significant overall two-way interactions between all main effects as K generally decreased by depth and had a lot of variability across the four years of observation (Table 2.3). In the LM treatment, K concentration in the 0-5 cm depth increased annually up to 2022, then it decreased in 2023, with all treatments having some level of decrease in 2023. The model for P was not significant for the overall two-way model with all main effects considered but year by depth without treatment considered (Table 2.3). Phosphorus did have treatment differences in the 0-5 cm depth (Table 2.4), and when comparing years, 2021 had statistically less than the other three years ($\alpha = 0.1$). Calcium also had no significant overall two-way model with depth used but individual interactions with treatment and depth along with year and treat was significant (Table 2.3). Calcium did have an effect by year regardless of treatment at 0-5 cm depth. It decreased statistically ($\alpha = 0.1$) from 2022 to 2023, but when treatments were combined, 2020 and 2021 were not different from any other year. Not surprisingly, K, had the greatest amount of variation based on years and treatments at a 0-5 cm depth likely reflecting its mobility in both plants and soil. Still, the pattern did not continue in 2023 as sampling time or fertilizer application variations from the previous season could have impacted concentration the next year. Samples for nutrients were taken prior to fertilizer application but fertilizer application rates varied from year to year based on soil samples collected prior to planting (range in years from 0-129 kg ha^{-1} K), leading to a possibility of a nutrient reservoir building in K in this case so when sampled, less was applied and the reservoir got depleted for the nutrients level moving back into a zone of higher application rate. The nutrients were also applied uniformly for the field and not based on specific treatment variations. Similarly, Ca and P had no treatment effects in the 0-5 cm depth and showed no connecting pattern in the year effect with minimal overall mean differences across years regardless of treatment.

Nutrient comparisons for the repeated measure pairwise analysis were done for data from 2021 to 2023 at the surface based on ANOVA (Table 2.3). Not surprisingly, nutrients decreased by depth as they were surface applied. The first year of the study was excluded because there was no complete sampling of all field replications in 2020. Pairwise comparisons without treatment separations but years had the same results with the changes across years for Ca, Mg, and P. The means were the same for the years 2021 to 2023 but 2021 to 2022 increased and 2022 to 2023 decreased, were different from the rest for nutrient concentration differences for the nutrients of Ca, Mg, and P. Manganese concentrations were similar between treatments and not statistically different, but 2021 was numerically greater than 2022 and 2023 when treatments were combined. The only treatment effect was in 2021 where K was statistically greater ($\alpha = 0.1$) in LM than CR when separated by year.

Challenges and Limitations

The challenge of quantifying changes in soil quality for soil health improvements has been studied in terms of the key properties that indicate change. Soil chemical properties showed little change with primarily just numerical trends when using all three main effects with two-way interactions (Table 2.3). Increases in TOC has been linked to changes in other soil properties (Allen et al., 2011; Blanco-Canqui et al., 2022; Delaune et al., 2019). This study had only numerical trends for TOC over time, which suggests either there was too much variability between replications or that there was simply insufficient time to see treatment effects. Carbon is a parameter included in many minimum soil health datasets because it affects properties like K_{sat} and bulk density (Hubbard et al., 2013). For example, the Soil Health Institute recently identified a set of important parameters for soil health assessment that included two carbon-based measurements, soil organic carbon and 24 h mineralizable C (Bagnall et al., 2023). One key takeaway from this study is that mineralizable N was greater in LM than other treatments in 2021. The other properties measured for changes in soil health for physical and hydraulic factors showed limited effects from the use of different cover crops. Many sources note changes taking eight years (Blanco-Canqui et al., 2023), while others measure changes after ten years of cover cropping (Chalise et al., 2019). Sufficient time is needed for measurable changes in soil health and variability in cover crop biomass over the years can affect the amount of time required to observe changes. For example, Blanco-Canqui et al. (2023) reported the biomass of cereal rye cover crop increased after four years possibly explaining why changes occurred later. Time likely being a key factor for changes to occur from cover crops draws attention to sampling method. Variability is soil physical properties were measured at single points in the field (e.g., hydraulic conductivity and bulk density) tend to fluctuate more over time than measurements made on composite soil samples from each treatment (i.e., aggregate stability). These fluctuations were likely connected to why minimum soil health properties are based in composite sampling that covers an area more easily and cost-effectively to get a representative sample (Bagnall et al., 2023).

The length of time necessary to see changes in soil physical and hydraulic properties varies by soil type and management. We found few significant differences over the four-year sampling time in this study, suggesting our soil was not sensitive to the evaluated cover crop systems after four years. This is similar to what Blanco-Canqui et al. (2023) and Chalise et al. (2019) found where eight years or longer may be necessary before changes in physical, hydraulic, and chemical soil properties are observed. The amount of measurable change in soil health indicators over time could be altered with increases in cover crop biomass (Blanco-Canqui et al., 2023). Another study in Piedmont soils of Maryland found that using a winter annual cover crop increased WSA after just two years (Steele et al., 2012). In the same geographic location as the present study but in corn cropping system, there was a statistical separation for bulk density, porosity, and water infiltration unlike the findings here (Hill et al., 2021). The CR and CC bulk density values were comparable to the initial treatments in Hill et al. (2021), but we did not observe changes in bulk density from LM as they reported. The soil porosity and K_{sat} had similar numbers except for no differences while this trial had greater overall K_{sat} and numerical improvement from LM as in Hill et al. (2021). The greater K_{sat} values overall may be due to different instruments used, with Hill et al. (2021) using a Guelph Permeameter vs the SATURO system used for this study. One reason our data may not have shown the same soil changes could be differences in management and growth patterns of cotton versus corn. Another factor is the differences in results found by Hill et al. (2021) had comparisons available for some properties with before the establishment of cover crops to when living mulch had time for impact while our study only included measurements during the time when the cover crop was established. Therefore, we conclude that it is imperative to have comprehensive control sample prior to the establishment of soil change studies.

Conclusions

Monitoring soil changes from cover crops in a no-till cotton production system was explored in this study. The main effect of sample depth was significant for many of the soil properties measured. In focusing in the upper soil samples from 0 to 5 cm as the impact zone connection between treatment over time interaction did not occur. The bulk density and wilting point decreased while the porosity and K_{sat} increased in the LM treatment compared to other treatments. There were no treatment effects on TOC or TON, however potentially mineralizable N was significantly greater in the LM treatment compared to the CO illustrating the importance of N contributions from the LM. The lack of TOC differences suggested there was insufficient time for cover crop impacts to be realized. The increase in K over time in the LM treatment after three years before decreasing in the fourth year highlights the potential of LM as a nutrient reservoir for this highly mobile macronutrient. Soil strength measurements clearly showed the presence of a tillage pan in all treatments though interpretations of treatment differences were hindered by differences in soil moisture. In conclusion four years of time was not long enough to see many measurable changes in the evaluated soil properties which suggests more time is needed for cover crops and no-till farming practices to measurably impact soil health indicators.

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Table 2.1. ANOVA table for bulk density (ρ_b), water stable aggregates (WSA), available water content (AWC), field capacity (FC), wilting point (WP), soil porosity (Porosity), and saturated hydraulic conductivity (K_{sat}) for four years with four treatments. Measurements made at the surface (IR) or 0 to 30 cm ($\rho_{b,}$ AWC, FC, WP, Porosity) with the depths split into 0-5, 5-15, and 15-30 cm. For WSA, the upper two depths were used. The four treatments were living mulch (LM), cereal rye (CR), crimson clover (CC), and bare ground (CO).

Coefficients	DF	ρ_b	WSA	AWC	FC	WP	Porosity	K_{sat}
Year (Y)	3	**	**	**	**	**	**	**
Treatment (T)	3	**	NS	**	**	NS	**	**
Depth (D)	2/1†	**	**	**	**	**	**	-
Y x T	9	*	NS	NS	NS	NS	**	*
Y x D	6/3	*	NS	NS	NS	NS	NS	-
T x D	6/3	NS	NS	NS	*	NS	NS	-

† DF for depth are for ρb, AWC, FC, WP, Porosity, and IR which have three depths whereas WSA has only 2 depths

**Significant effect (α=0.05)

*Significant effect (α=0.1)

Table 2.2. Four-year (2020-2023) measurements of volumetric available water content (AWC), volumetric field capacity (FC), volumetric wilting point (WP), soil porosity (Porosity), water stable aggregates (WSA), and saturated hydraulic conductivity (K_{sat}) for surface soils in four treatments. The four treatments were living mulch (LM), cereal rye (CR), crimson clover (CC), and bare ground (CO).

Treatment	Year	AWC	FC	WP	Porosity	WSA	(K_{sat})
			$cm^3\ cm^{-3}$		-----%-----		$cm\ hr^{-1}$
CO	2020	0.13	0.20	0.07	47†A	97	6.9
	2021	0.08	0.17	0.09	45ab	91	11.3b
	2022	0.14	0.20	0.06	43	97	8.7
	2023	0.11	0.18	0.07	42	97	7.5
CC	2020	0.17	0.25	0.09	42B	97	5.0
	2021	0.08	0.14	0.09	47ab	98	7.1b
	2022	0.08	0.17	0.09	41	97	14.6
	2023	0.11	0.18	0.08	45	96	11.2
CR	2020	0.14	0.22	0.08	42B	95	3.0
	2021	0.11	0.17	0.09	44b	94	13.3b
	2022	0.09	0.18	0.09	38	98	3.0
	2023	0.12	0.19	0.07	42	98	8.5
LM	2020	0.12	0.18	0.06	45AB	94	4.1
	2021	0.17	0.24	0.07	52a	94	25.3a
	2022	0.09	0.16	0.07	44	98	17.9
	2023	0.12	0.18	0.07	44	98	16.5

†Significantly different (α=0.1) within year between treatments indicated by uppercase letters for 2020 and by lowercase letters for 2021 per each property separate

Table 2.3. ANOVA table for Mehlich 1 extractable nutrients, total organic carbon (TOC) and nitrogen (TON) from combustion, and calculated water soil pH of soils for four treatments across four years. Measurements from three depths split into 0-5, 5-15, and 15-30 cm. The four treatments were living mulch (LM), cereal rye (CR), crimson clover (CC), and bare ground (CO). Water pH was calculated from calcium chloride pH (Kissel & Sonon, 2008).

Coefficients	DF	Mehlich 1 Nutrients								
		pH	Ca	K	P	Mg	Mn	Zn	TOC	TON
Year (Y)	3	**	**	**	**	**	**	**	NS	**
Treatment (T)	3	*	NS	**	**	**	**	NS	NS	*
Depth (D)	2	**	**	**	**	**	**	**	**	**
Y x T	9	**	**	**	NS	NS	NS	NS	NS	*
Y x D	6	NS	NS	**	**	**	**	**	NS	NS
T x D	6	NS	**	**	NS	**	NS	NS	NS	NS

**Significant effect (α=0.05)
*Significant effect (α=0.1)

Table 2.4. Mehlich 1 extractable nutrients, total organic carbon (TOC) and nitrogen (TON) from combustion, and calculated water soil pH of surface soils (0-5 cm) for four treatments across four years. The four treatments were living mulch (LM), cereal rye (CR), crimson clover (CC), and bare ground (CO). Water pH was calculated from calcium chloride pH (Kissel & Sonon, 2008).

Treatment	Year	pH	Mehlich 1 Nutrient						TOC	TON
			Ca	K	P	Mg	Mn	Zn		
			----------------------mg kg^{-1}--------------------						------%------	
CO	2020	6.4	804	101	49	66	50	2.9	1.32	0.12
	2021	6.7	814	123	38	67	39	3.9	1.15	0.12
	2022	6.7	853	130	57	74	18	5.0	1.08	0.11
	2023	6.3	790	119	45	73	20	4.2	1.28	0.12
CC	2020	6.6	956	105	49	66	59	3.5	1.21	0.12
	2021	6.5	756	107	31	62	41	3.6	1.20	0.12
	2022	6.5	862	107	51	74	28	4.5	1.21	0.12
	2023	6.3	684	95	41	60	20	3.5	1.17	0.11
CR	2020	6.3	834	117	53	57	67	4.4	1.43	0.13
	2021	6.4	665	97*	29	56	45	4.2	1.14	0.11
	2022	6.5	841	98	47	70	23	5.1	1.10	0.10
	2023	6.2	684	96	35	59	21	4.3	1.31	0.11
LM	2020	6.3	757	106	55	53	54	3.7	1.24	0.11
	2021	6.5	862	136*	40	69	47	4.3	1.32	0.14
	2022	6.6	912	160	51	75	29	4.4	1.34	0.14
	2023	6.3	811	106	45	73	24	4.0	1.59	0.15

* Indicates significant difference (α=0.1) between treatments of CR and LM for the nutrient concentration of K.

Table 2.5. Mineralizable nitrogen in 30 days in spring samples taken in 2021 and 2022 from four treatments at a depth of 0-5 cm after cover crop termination but prior to fertilization and cotton planting. The four treatments sampled include living mulch (LM), cereal rye (CR), crimson clover (CC), and bare ground (CO).

Treatment	Mineralizeable N	
	mg kg^{-1}	
	Year	
	2021	2022
CO	1.8*	1.4
CC	2.4	1.5
CR	2.8	1.5
LM	4.2*	2.6

* Indicates significant differences (α=0.1) between treatments mineralizable nutrient concentration differences within year

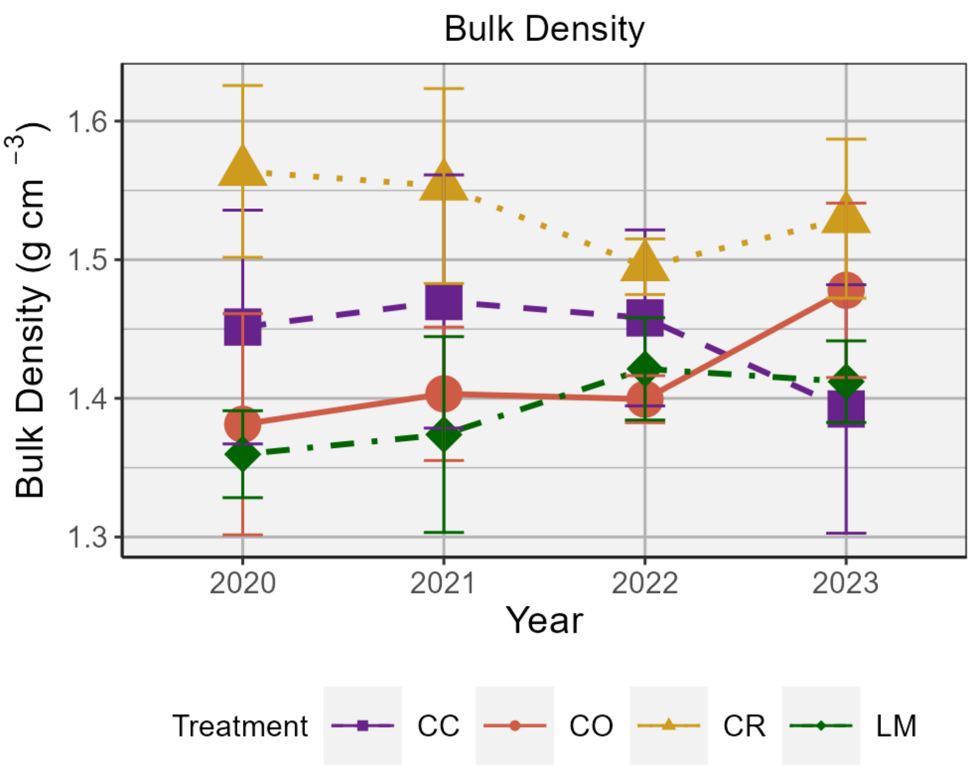

Figure 2.1. Bulk density from 0-6 cm depth of four cover crop treatments over four years measured a few weeks after the planting of cotton. Treatments were living mulch (LM), cereal rye (CR), crimson clover (CC), and bare ground (CO). Error bars represent standard error.

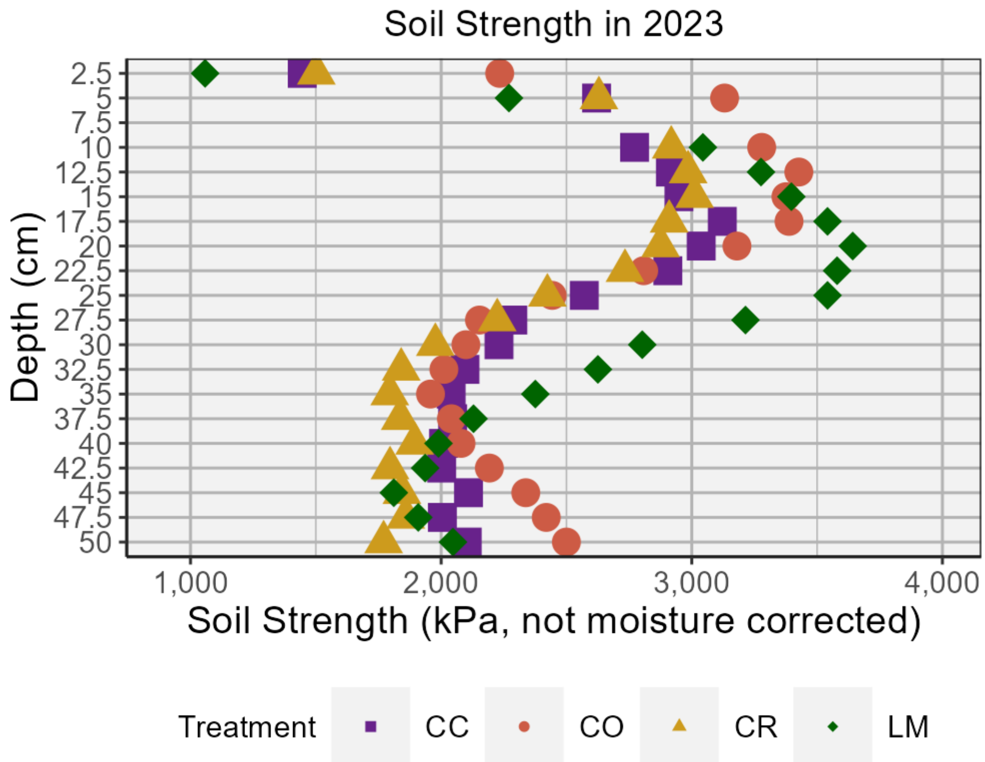

Figure 2.2. Soil strength in 2023 from the surface to 50 cm as impacted by the treatments of living mulch (LM), cereal rye (CR), crimson clover (CC), and bare ground (CO) in a cotton field a few weeks after planting. The graph is not moisture corrected, but at 9-15 and 19-25 cm LM had a significantly lower soil moisture than other treatments (α=0.1).

CHAPTER 3

ANALYSIS OF SOIL PROPERTY CHANGES OVER TIME IN A PERENNIAL COVER CROP LIVING MULCH SYSTEM IN GEORGIA COASTAL PLAIN SOILS

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Abstract

Management practices that improve or maintain soil health and function are important for a variety of cropping systems. One proven way to enhance soil health is by using cover crops which have many benefits including keeping the soil covered, increasing organic matter, and reducing weed pressure. Most cover crops are annual species, but perennial cover crops have recently been shown to outperform annual species when considering soil health improvements. This study aimed to evaluate changes in soil health properties from a perennial cover crop over a three-year period in two diverse cropping systems. A perennial white clover (Trifolium repens var. 'Durana') cover crop was established as a 'Living Mulch' (LM) in two contrasting production systems row cropping (RC) and a newly established pecan orchard (PO). Monitored soil properties included bulk density, aggregate stability, water infiltration rate, water retention, pH, total organic carbon/nitrogen, and Mehlich 1 nutrients. Total organic carbon (TOC) in the upper 0-5 cm increased over time by a total of 0.34% in the three years of the RC and by a total of 0.47% in the three years of PO. The LM provided an opportunity to curb the impact from farm equipment in PO by increasing water infiltration rate by 15 cm hr^{-1} in lower wheel traffic relative to high wheel traffic area after three years. In the three-year measurement period, bulk density significantly increased in RC and showed no change in PO whereas changes in other physical properties were limited. Detecting changes in soil health usually takes time, but these few early indicators show potentially important changes from using LM systems.

Key words: Soil Health, Living Mulch, Total Organic Carbon, Water Infiltration Rate

Introduction

Improvements in physical, chemical, and hydraulic soil properties are desired outcomes from the utilization of long-term cover cropping strategies. Cover-cropping effects on soil health are commonly monitored by measuring properties such as bulk density, aggregate stability, macro- and micro-nutrients, total organic carbon (TOC) and nitrogen (TON), available water content, and water infiltration rate among others (insert citations for these). Sufficient time is required to observe meaningful changes in dynamic soil properties often measured to quantify soil health. As such, long-term cover cropping strategies are desired to see the effects from cover crops (Blanco-Canqui et al., 2023; Hill et al., 2021; Nouri et al., 2019). Because long-term cover crop use is required to improve soil properties, one strategy to get more benefits in less time is to use perennial cover crops. Cover crops working year-round in a perennial system have more time than annual cover crops that are only grown for a portion of the year. The perennial cover crop commonly used in Georgia cropping systems is white clover, a common forage legume which when used as a cover crop is referred to as a living mulch system (LM). White clover is divided into three types: large, intermediate, and low growing; the desired one for perennial cover cropping system is Durana clover (*Trifolium repens*), an intermediate type. Intermediate clover varieties are known for being suited for most of Georgia because they are prolific reseeders and produce ample stolons to regenerate each year making it ideal for perennial cover crop use (Andrae, 2009).

The proof of concept for incorporating a LM in southeastern cropping systems has been established for the use of the perennial white clover systems (Andrews et al., 2020; Andrews et al., 2018; Hill et al., 2021; Sanders et al., 2018; Sanders et al., 2017; Weisberger et al., 2024; Quinby et al., 2023a; Quinby et al., 2023b). In these studies, N and water use were the main focus as they are key dynamics when growing two plants in a field at the same time. Other benefits include keeping the ground covered and weed suppression (Andrews et al., 2018; Sanders et al., 2018; Sanders et al., 2017; Weisberger et al., 2024). The LM system can also provide N to the soil throughout the season as compared to annual cover crops (Hill et al., 2021). The focus on more physical and hydraulic soil properties in cropping systems as affected by cover crops, specifically perennial cover crops, is limited in information to multiple properties focusing on physical and hydraulic soil properties (Hill et al., 2021).

Soil physical properties do not always respond to cover crops, as illustrated in a meta-analysis of 98 peer-reviewed papers by Blanco-Canqui & Ruis (2020), who found about one-third of studies reported a reduction in bulk density. For other physical parameters, there were more promising improvements with 65% of studies showing reduction penetration resistance and 52% of studies finding increased water-stable aggregates. Still, annual cover crops are common and time in cover cropping is needed to promote changes to soil health (Blanco-Canqui & Ruis, 2020). Soil types often influence the response of soil properties. For example, Steele et al. (2012) found that the impact of cover crops on water-stable aggregates was different in sandy soils of the Coastal Plain compared to the finer textured Piedmont soils. The same soil locations also had lower bulk density reduced with cover crops when in the non-growing season, which had residual effects in the second year in Coastal Plain soil (Steele et al., 2012). The use of cover crops increased the labile C, which affected the physical parameter of increased water-stable aggregates (Steele et al., 2012). The connection between the properties is clear and more defined in Coastal Plain soils that allow for long-term improvements in physical and hydraulic properties (Çerçioğlu et al., 2019; Nouri et al., 2019; Steele et al., 2012).

While physical and hydraulic properties can be improved from cover crops, many of them are closely connected to soil C and organic matter content. One advantage of cover crops compared to no ground cover or fallow systems is the production and incorporation of more biomass, with the greatest advantage being the added N and C to the soil (Sainju et al., 2002). Pasture will have higher soil carbon in the Piedmont and Coastal Plain soil that can be built but conventional tillage row crop field is lower and easier to make improvements through management changes like conservation tillage (Causarano et al., 2008). Another cover crop grown annually planted in the winter is cereal rye (*Secale cereale*), a high biomass crop that is high in C but low in N, resulting in a higher C/N ratio. Increases in soil organic C from the cereal rye are one benefit, while other benefits from the roots cause an increase in infiltration with a reduction in penetration resistance (Delaune et al., 2019). These changes in infiltration and penetration resistance reflect altered soil structure and water-stable aggregates, which are affected by changes in the amount of C in the soil (Hubbard et al., 2013; Liu et al., 2005; Steele et al., 2012). In the soil surface, gaining better infiltration from improved soil structure and aggregation is often reflected in reduced bulk densities and better soil infiltration and water retention when cover crops are used (Chalise et al., 2019; Rankoth et al., 2021).

Residues from crop rotation or cover crops have varying dynamics that need to be managed. Microbial biomass needs N added or supplied by the system to break down C in residues and increase soil organic matter (SOM) in long-term practices (Villamil et al., 2006). Legume crops provide N, and rotations with legume crops or legume cover crops provide N needed to break down residues to increase soil fertility. Short-term use of cover crops for one year has proven not to provide the same soil health benefits that may be realized after multiple years of cover crop use (Acuña & Villamil, 2014; Villamil et al., 2006; Villamil et al., 2008).

Macro-nutrients of phosphorus (P) and potassium (K) used in tillage vs. non-tillage, and fertilizer increases do not significantly impact yield when starting on soil at adequate levels (Yuan et al., 2020). No-till is more likely to maintain better soil moisture near the soil surface, making K more available. Changes in the soil to improve physical and hydraulic parameters result in plants having an added advantage for utilizing fertilizers, especially at critical times for the crop (Mackay et al., 1987). Changes in nutrient availability, including P, are linked to soil pH. The reduction in soil pH as a cover crop breaks down in connection to soil organic matter dynamic changes can cause increased P availability (Vanzolini et al., 2017) although responses are dependent on initial soil conditions, soil type, etc.

The specific focus of this study was to quantify changes in dynamic soil properties over three years for two contrasting management systems (row crop and pecan orchard) that included a continuous white clover LM in the Coastal Plain Physiographic region of Georgia, USA. An overarching hypothesis was that there would be changes in the most sensitive soil health indicators in a three-year period including bulk density, aggregate stability, infiltration rate, and total organic carbon. Furthermore, we expected differences in the magnitude of these responses by management type.

Materials and Methods

A white clover LM treatment was measured and monitored at two locations in the Georgia Coastal Plain that both had irrigation managed by each location's respective crop needs decided by farm managers. The first location (RC) was at the Southeast Georgia Research and Extension Center in Midville, GA (32.878783 N, -82.215920 W) where a cotton cash crop first year and corn cash crop for the next two years. The soil was classified as Dothan loamy sand (Soil Survey Staff, 2019; Soil Survey Staff et al., 2019). The 1-hectare area was split into two treatment zones. One area had 'Durana' white clover (*Trifolium repens* L.; Bouton et al., 2005) established in fall of 2018 and managed for LM for three subsequent years (LM3), and the other area had a cereal rye (*Secale cereal*) cover crop planted in the fall of 2018 that was terminated before cotton planting in May 2019. The area planted to cereal rye was changed to a LM system in the fall of 2019 and managed for LM for two subsequent years (LM2). Corn was planted in April of 2020 and 2021. The second site (PO) was a pecan orchard that had been recently established near Stapleton, GA on a private farm. Site history included the harvest of mature pine trees in approximately 2018, followed by the establishment of a white clover in April 2019. Two sites at the PO site were monitored for three years (2021-2023): The first site (P1), was mapped as a Clarendon loamy sand and the second site (P3) was mapped as an Orangeburg loamy sand (Soil Survey Staff, 2019). The P1 location had greater soil water content throughout the year and a lower elevation compared to the P3 location.

Monitoring plots (hereafter referred to as a cluster) were established for multiple locations at each site to represent soil variability and treatments effects. There were two clusters at each RC treatment and one cluster for each soil evaluated at the PO site. At each sample location, the plot design was comprised of two to four points sampled 4 m from the center location in the four cardinal directions for the collection of bulk density, infiltration rate, aggregate stability, and water retention cores. Composite samples (n = 10) were taken from a 6 m x 6 m area surrounding each center point using a push probe and separating samples by 0-5 cm, 5-15 cm, and 15-30 cm depths. In both PO locations, two of the four points in a cluster had wheel track impacts from farm equipment (primarily sprayer traffic) and two points were outside of the tractor equipment path. Analysis of the wheel track impact is described in the statistical procedure below. A total of four clusters were sampled at the RC site annually from the spring of

2019 through the spring of 2021 on multiple sampling points in the two areas. The PO site was sampled in the spring of 2021 to 2023 on the two contrasting soils.

Composite samples were air-dried and sieved (2 mm) for further analysis (hereafter referred to as the AD composite samples). Chemical analyses included Mehlich 1 extractable nutrients (P, K, Mg, Zn, and Mn), and 1:1 soil:water pH, and buffer capacity (Kissel & Sonon, 2008). The soil water pH was approximated by adding 0.6 units to calcium chloride pH following Kissel and Sonon (2008). For total organic C and N (TOC and TON, respectively), ~8 g subsamples of AD composite samples were ball-milled and then subsampled to be prepared for analysis by dry combustion (Bremner, 1996). Soil texture was measured for 0.5 g subsamples following dispersion with 5 ml of sodium hexametaphosphate (50 g L^{-1}) using a Beckman Coulter Laser particle size analyzer (Beckman Coulter LS 13 320, Indianapolis, IN). Water stable aggregates (WSA) were determined using 4 grams of the AD composite samples that were pre-wetted using a humidifier before analysis using a wet-sieving method on (Kemper & Rosenau, 1986). Bulk density was sampled using a slide hammer with a multi-stage section sleeve 5.08 cm wide and separated into 0–5 cm, 5–15 cm, and 15–30 cm depths with 2–4 replicates taken at each cluster.

Soil hydraulic properties of interest were water content at both field capacity (0.03 MPa; FC) and the wilting point (1.5 MPa; WP) and surface infiltration rate. Undisturbed soil cores (volume 135.8 cm^3) were taken from each plot at the surface (0–6 cm), upper root zone (9–15 cm), and lower depth (19–25 cm) to determine field capacity with a Tempe cell set up (SoilMoisture Equipment Corp., Santa Barbara, CA). Following FC measurement, a portion of the same sample was used to determine the water content at the WP using a WP4C (Meter Group, Inc. USA). Plant available water capacity (AWC) was determined as the difference in FC and WP and was expressed on a volumetric basis. Surface water infiltration (IR) was measured using a 15-cm diameter single-ring placed 3 cm deep in the soil, and a 3 cm constant-head was maintained with a custom Mariotte bottle described by Herrick et al. (2005) with two to four replicates per cluster.

All statistical procedures were performed in R studio version 2023.12.0 using R version 4.3.2 with the rstatix, dplyr, ggplot2, and tidyverse packages for ANOVA and pairwise t test with paired samples for repeated measures as additional analysis along with unpaired (Kassambara, 2023; R Core Team, 2021; Wickham H, 2016; Wickham H et al., 2019; Wickham H et al., 2023). Comparisons between treatments and years with RC and PO sites were analyzed separately, with comparisons between years with treatments within location combined along with comparisons between treatments with years combined using ANOVA with replicate as a random effect. The pairwise t-test was used as the samples were taken from the same location each year, making them a paired sampling method. Infiltration rate analysis had a wheel track impact by years, and between years, treatment of P1 and P3 locations was replaced for the PO trial to analyze the comparison of the wheel track impact for only infiltration rate.

Results

Soil Metrics at the Row Crop Site

Data analyzed by depth had inconsistent changes from year to year with treatment in the 5-15 cm depth not having significant differences (Table 3.2). The lowest depth of 15-30 cm had only differences from time being in LM3 treatment increase in 2021 while LM2 in 2020 was significantly lower in bulk density (Table 3.2). Bulk density was the only property in RC to have a significant three-way interaction (not shown), and the two-way interaction of treatment and depth was significant (Table 3.1). Infiltration rate had significant interactions between year and treatment, while no other physical property had an overall significant two-way model with depth included as a factor (Table 3.1). Results are therefore focused on the upper 0-5 cm as the most likely zone to be affected by the LM treatment. The bulk density had statistical differences, but the properties of water infiltration rate that were closely related had interaction differences indicated by the ANOVA (Table 3.1). The bulk density had a significant increase over time in LM2 and a lowering in bulk density then back to a statistically comparable value in the final year for the LM3 treatment (Table 3.2). Infiltration rate fluctuated from year to year as indicated by the significant interaction between year and treatment (Table 3.1). Similarly, the infiltration rate of LM2 statistically increased from 2019 to 2020 (not shown). There were no changes in soil porosity or AWC with an average across all samples was 0.41 $cm^3\ cm^{-3}$ and 9 $cm^3\ cm^{-3}$, respectively (Table 3.2). Depth had no significant impact with treatment and year for AWC, FC, and WP for these hydraulic properties measured (Table 3.1). Using the largest amount of data from all three depths does not clearly indicate FC or WP being the main influence in the calculated value of AWC, with none of the three properties having significant models (Table 3.1). The porosity measured from Tempe cells had a similar but not as strong of an effect from clay increase, impacting the measurement by depth. Water-stable aggregates had no significant interactions and limited variability, as shown in the range of means being 9% when using all three depths (Table 3.1).

Of the measured soil chemical properties, only Zn did not have at least one significant two-way interaction and most of the interactions involved depth (Table 3.3). The range of pH across all depths and RC treatments was 1.3 with a mean of 6.3, with most of the values all being in the same limited range that nutrients would all be available for agronomic interpretations

(Table 3.4). When evaluating the surface data 0-5 cm depth, the TOC significantly increased regardless of treatment from year one to year three in the RC trial (Table 3.4).

Soil Metrics at the Pecan Orchard Site

Including all three depths, bulk density had a main effect of depth similar to the RC trial but without interactions (Table 3.1 & 3.5). The PO site had limited main effects impacts with no interactions for physical properties besides the soil and depth interaction for bulk density (table 3.5). Water-stable aggregates represented composite samples from each of the soils (n=1) which didn't allow for an ANOVA, though single point comparisons are shown in Table 3.5. Hydraulic parameters of AWC, FC, and WP all had a treatment effect and did not have any interactions (Table 3.5). Soil porosity in the 0-5 cm significantly increased in 2023 compared to other years at the P1 location (wet site) and P3 (dry site) had a numeric increase for 2023. These samples were taken from a different core than bulk density. The AWC at P3 increased significantly at the 0-5 cm depth from 2021 (0.10 $cm^3\ cm^{-3}$) to 2023 (0.18 $cm^3\ cm^{-3}$) to, but there were no significant changes in AWC over time at the P1 location (Table 3.7). Aggregate stability at the 0-5 cm depth was not impacted by treatment but did differ by year, with the aggregates being significantly the greatest in 2021 at 92% WSA and 76% and 72% WSA for 2022 and 2023, respectively, with a standard error of 3.2 (data of combined by treatments not shown).

This section on soil nutrients focuses on the upper soil sampled depth from 0-5 as the area most likely to have impacts from management. From 2021 to 2023, K increased statistically from 112 to 153 mg kg^{-1} when the treatments that had no difference were combined. Mg and Zn had a trend similar to K over time with an increase from 2021 to 2022 and remained higher than in previous years (Table 3.6). Manganese (Mn) did the opposite, decreasing statistically from 2021 (32 mg kg^{-1}) to 2022 (25 mg kg^{-1}) and then to 2023 (16 mg kg^{-1}; Table 3.6). The pH was at an average of 6.57 with a range of 0.49, making nutrient availability not an issue for the plants, with the measured added Mehlich 1 nutrients that are beneficial for cash crop production. The location was not a factor for differences in all nutrients, but P was statistically greater in the more well-drained site (P3) than in the wetter site (P1) every year. The changes could also be connected to the steady increase in TOC and TON from 2021 to 2023 (Table 3.6) when soils that had no difference were combined.

Wheel Track Impact on Soil Properties at the Pecan Site

Infiltration showed no significant differences by treatment at the Pecan trial barring measurements at the P1 site in 2023 when the soil was saturated at the time of sampling. The measurements taken between the main wheel tracks had a faster infiltration (29 cm hr^{-1}) compared to the wheel track (14 cm hr^{-1}) when combining all years. While the difference of wheel tracks vs. between wheel tracks was significant in 2021, values were not significant beyond the first year. (Figure 3.2). In 2021, infiltration between wheel tracks was 39 cm hr^{-1}, which significantly decreased to 6 cm hr^{-1} in the wheel tracks.

Comparisons and Discussion

The LM treatment had limited effects on measured soil properties in the RC and PO locations over the three-year sampling periods. There were limited changes to soil properties in RC production system using LM, but irrigation to keep the stand established was a key factor that changed measurements taken from nutrient changes in the RC site. The PO site was managed differently with a more generous amount of irrigation applied throughout the year resulting in an ideal environment for LM cover crop.

An effect in the PO trial from tractor tire impact occurred as the same driving path was used every time year after year. The lack of impact on soil series on bulk density, infiltration, porosity, and AWC properties is predictable from the coastal plain soils being sandier in soil texture in PO. The RC had more differences than the PO as the RC had bulk density having interactions. A study comparing the variability between sandy loam and loam soils had similar AWC to both PO and RC studies (Duffera et al., 2007). The comparison between total porosity was similar across years and treatments, but there was a weak trend of increasing AWC in the LM cover crop. Another comparison with row crop agriculture and pine trees for production in Georgia reported similar results for the soil physical measurement bulk density (Levi et al., 2010). Still, it did not explicitly evaluate the impacts of cover crops but had one overlapping soil series of Orangeburg with PO trial others similar in being South Georgia Coastal Plain soil (Levi et al., 2010). Water-stable aggregates in not disturbed soil like no-till fields similar to the Pecan site were similar in being greater than 90% for the first year to the study of Levi et al. (2010), but in 2022 and 2023, lower WSA is similar to row crop measurements (Table 3.2 & 3.7). The RC site being a row crop provided a comparison for the cropping system, but the differences in the duration of LM provided an opportunity for improvements that would not have been observed in Levi et al. (2010). Another similar study in the southeastern US did not find differences in aggregate stability for different cover crops on two different soil types after four years with one of them being in the Coastal Plain soils (Decker et al., 2022).

The infiltration rates measured at the PO and RC sites were similar in magnitude to those reported for a row crop site on a similar soil of the Coastal Plain (Satiel et al., 2022). Infiltration rates measured in this study were also similar to those reported by Levi et al. (2010) for another set of similar soils in the Coastal Plain. One possible reason for variability between studies could be differences in measurement techniques as reported by Satiel et al. (2022). Other differences in infiltration rates may be a result of interactions between residue from cover crops and the subsequent impacts on bulk density (Chalise et al., 2019). The bulk density at the PO trial had a decreasing trend over time, whereas the RC plots had the opposite trend which may be a result of more machine traffic at the RC site to manage cover crops, cotton, and corn.

A noticeable management effect developed in the RC field in 2021; the upper and lower parts of the field had different stands of living mulch. This was likely an irrigation issue from the center pivot, and with the low AWC range not having the moisture to maintain the two plants, row crop and living mulch cover crop, growing at the same time prevents the ability of living mulch cover crop to survive and create changes. The lower part of the field had a greatly reduced stand of LM cover crop. This indicates that management can significantly alter dynamic soil parameters like bulk density, soil carbon, aggregate stability, and water retention, and many of them are interconnected; therefore, it is important to monitor them to detect changes over time (Bagnall et al., 2023). While management can influence properties, sufficient time is needed for many changes from cover crops. In the three years of measurements in PO and RC trials, neither reached the eight years that Blanco-Canqui et al. (2023) stated is needed for many soil properties at their location in Nebraska to have a change in properties. Also, it is important to note that there were no differences from initial measurements at three years, but patterns of soil change varied by management and soil type suggesting different timelines for change. Many properties take more than four years to change appreciably but it may take longer (e.g., Blanco-Canqui et al. (2023) suggested eight years were necessary to see differences). In contrast, Hill et al. (2021) reported a decrease in bulk density when in a LM cover crop after three years on a fine textured soil in the Georgia Piedmont.

The soil physical measurements that indicate soil structure, namely bulk density, porosity, and aggregate stability having limited variability in the measurements over the three years in considering both trials directly relate to the relationship between the physical and hydraulic treatments connections. Another way to create changes in soil properties is through chemical changes affecting soil properties. The pH and Mehlich 1 extracted nutrients of K, Mg, Ca, and P at the north Georgia site of Hill et al. (2021) was greater in the LM treatment compared to other treatments but compared to our RC trial on the Georgia Coastal Plain soil did not have the same response with having greater nutrients constantly over time. The TOC did have the same response with building over time in both the RC and PO trials, similar to Hill et al. (2021). The TOC building over time can provide a binding site for cation extractable nutrients in the soil. Soil C building in grazed pastures located on Georgia Piedmont soil at a greater rate than conventional tilled cropland has that connection to the no-till and pasture-like ground coverage found in the LM system used in this study (Franzluebbers et al., 2000). These increases in soil C are speculated to improve the natural soil fertility of the land (Franzluebbers et al., 2000).

Varying responses over time in soil properties at the trials are connected to soil series and time of treatment applied, culminating in the site-specific response to what is categorized as soil health indicators (Bagnall et al., 2023; Blanco-Canqui et al., 2023; Chalise et al., 2019; Hill et al., 2021). The utilization of winter cover crops on Atlantic Coastal Plain soil, similar to other literature, decreased bulk density and infiltration in Maryland (Steele et al., 2012). Cover cropping and no-till being a strategy to achieve improved soil health have many parameters used and different ways to determine what are the best indicators of change in time. Having the fewest items to measure while still accurately quantifying the change in the soil health is challenging, and for different soils, it requires observations to know what is the most sensitive to responses (Bagnall et al., 2023). A minimum set of three soil properties is desirable to select and comparable to our trials with two of them were measured in both the RC and PO trials as they are sensitive to management changes, including aggregate stability and soil organic carbon (Bagnall et al., 2023). The RC and PO had improvements in TOC, but the WSA did not have the same response due to lack of variability from treatments. A few properties are selected for efficiency, so as not to repeat measurements and to affect time and cost. The use of additional measurements can aid in creating a full perspective of the impacts of the using cover crops, as well as repeating measurements and the interrelatedness of many measurements. An increase in organic matter, as shown in both the RC and PO sites, can lead to long-term effects on bulk density as soil organic C is a major factor impacting bulk density (Heuscher et al., 2005). Changing soil structure from increased organic matter affects water infiltration rates and water retention. Increased cation exchange capacity that occurs with the increased organic matter is also important for soil productivity (Tipping et al., 2016). The focus on soil surface properties is also supported by the importance of C having the greatest improvements in soil health indicators from cover crops in the Southeastern USA (Causarano et al., 2008; Decker et al., 2022).

The comparison by depth for bulk density had a significant three-way interaction of the main effects for the RC trial was predictable as with depth there is a clay content increase being the driving force as opposed to the treatments. Additionally, the RC treatments were only slightly different from one another. There was a similar pattern in the PO trial, but the clay increase by depth was less pronounced in PO compared to the RC trial (Table 3.1 & 3.5). The infiltration rate effects in the PO trial also have a likely common occurrence in the results that can be explained. The likely result of changes over time in the longer the field is established, and no-tillage or soil disturbance, just more wheel track passes of different equipment have different impact zones from the main tractor wheel track pulling sprayer that was a primary influence. The numerical trend of lower bulk density between wheel tracks for 2021 and 2022 links the connection of compaction and why there was a significant difference in 2021 for infiltration. Other measurements of WP and FC, being the parameters that calculate AWC, had similar patterns in response, as shown by the ANOVA results (Table 3.5). The same pattern for WP and FC with the AWC also being the same in ANOVA significance pattern gives an indication that FC or WP which both have some variability from time, treatment, and depth that neither are the main driving force in AWC (Table 3.5).

Conclusions

Total organic carbon was an indicator of soil changes in both trials at the soil surface. Over time, the increase in TOC from the LM treatment happened in all locations measured at the soil surface. The lack of response in other parameters may reflect the lack of time in the LM treatment after three years. The infiltration rate did not have a response over time, but wheel tracks from tractors in the PO trial resulted in predictable change resulting from compaction. However, the LM lessened the effect of compaction from wheel traffic in infiltration rate. The lack of time using LM can be an influence of why parameters are not being impacted over time from the cover cropping. This illustrates the understanding that time is needed to be passed along to users of the LM system of cover cropping and quick changes are limited to be observed in the short term.

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Table 3.1. ANOVA table for three years in row cropping trial with two treatments for comparison of bulk density (ρ_b), water stable aggregates (WSA), volumetric available water content (AWC), volumetric field capacity (FC), volumetric wilting point (WP), soil porosity (Porosity), and infiltration rate (IR). Measurements at the surface (IR) or 0 to 30 cm (ρ_b, WSA, AWC, Porosity) that was split by 0-5, 5-15, and 15-30 cm. The treatments within the location of living mulch (LM3), cereal rye in 2019 and LM grown after (LM2).

Coefficients	DF	ρ_b	WSA	AWC	FC	WP	Porosity	IR
Year (Y)	2	**	NS	NS	NS	NS	NS	NS
Treatment (T)	1	NS	NS	NS	NS	NS	NS	NS
Depth (D)	2	**	NS	NS	NS	NS	NS	-
Y x T	2	NS	*	NS	NS	NS	NS	*
Y x D	4	NS	NS	NS	NS	NS	NS	-
T x D	2	**	NS	NS	NS	NS	NS	-

** Significant at α= 0.05

* Significant at α= 0.1

Table 3.2. Bulk density (ρ_b), water stable aggregates (WSA), volumetric available water content (AWC), volumetric field capacity (FC), volumetric wilting point (WP), soil porosity (Porosity), and infiltration rate (IR) measurements for three years in row cropping trial with two treatments for comparisons. Measurements at the surface (IR) or 0 to 30 cm (ρ_b, WSA, AWC, FC, WP, Porosity). IR was averaged over measurements with prewetting in 2020 and 2021, with 2019 being averaged between prewetting soil and not. The treatments within the location of living mulch (LM3), cereal rye in 2019 and LM grown after (LM2).

Depth	Treatment	Year	ρ_b	WSA	AWC	FC	WP	Porosity	IR
			g cm^{-3}	%	---cm^3 cm^{-3}---			%	cm h^{-1}
0-5	LM3	2019	1.35†AB	99	0.12	0.16	0.05	40	14
		2020	1.17B	98	0.11	0.14	0.03	41	5‡a
		2021	1.37A	91	0.12	0.17	0.05	41	14
	LM2	2019	1.30AB	99	0.09	0.14	0.04	41	7
		2020	1.37AB	92	0.08	0.12	0.03	43	19b
		2021	1.42A	99	0.12	0.17	0.05	42	25
5-15	LM3	2019	1.53	99	0.08	0.14	0.06	33	-
		2020	1.37	97	0.12	0.16	0.04	38	-
		2021	1.47	98	0.08	0.14	0.05	36	-
	LM2	2019	1.52	100	0.11	0.14	0.03	35	-
		2020	1.44	93	0.06	0.11	0.05	39	-
		2021	1.50	98	0.08	0.14	0.05	36	-
15-30	LM3	2019	1.51AB	-	0.12	0.18	0.06	33	-
		2020	1.39AB	-	0.09	0.14	0.05	35	-
		2021	1.59A	-	0.11	0.15	0.05	31	-
	LM2	2019	1.55AB	-	0.13	0.17	0.04	33	-
		2020	1.37B	-	0.02	0.07	0.05	43	-
		2021	1.44AB	-	0.11	0.16	0.05	34	-

†Indicates significant difference (α=0.1) between treatments and years with depths analyzed separately with uppercase letters

‡Significant difference displayed by lowercase letters (α=0.1) between treatments within year

Table 3.3. ANOVA table for three years in row cropping trial with two treatments for comparison of Mehlich 1 extractable nutrients and calculated water soil pH from calcium chloride measured by years for row cropping system with two locations within for comparisons at depths of 0-5, 5-15, and 15-30 cm. The treatments sampled include living mulch (LM3), cereal rye in 2019 and LM grown after (LM2).

Coefficients	DF	pH	Ca	K	P	Mg	Mn	Zn	TOC	TON
Year (Y)	2	NS	NS	*	NS	NS	**	NS	**	**
Treatment (T)	1	**	NS	NS	NS	NS	**	NS	**	**
Depth (D)	2	NS	**	**	**	**	**	**	**	**
Y x T	2	**	**	NS	NS	*	NS	NS	NS	NS
Y x D	4	**	**	**	*	NS	NS	NS	**	**
T x D	2	**	NS	NS	*	NS	*	NS	NS	**

** Significant at α= 0.05

* Significant at α= 0.1

Table 3.4. Mehlich 1 extractable nutrients, and calculated water soil pH from calcium chloride measured by years for row cropping system with two locations within for comparisons at depths of 0-5, 5-15, and 15-30 cm. The treatments sampled include living mulch (LM3), cereal rye in 2019 and LM grown after (LM2).

Depth	Treatment	Year	pH	Ca	K	P	Mg	Mn	Zn	TOC	TON
			Mehlich 1 Nutrient								
cm				----------------mg kg^{-1} -------------						----%----	
0-5	LM3	2019	6.5	411	93	19	68	14	2.0	0.65†B	0.08
		2020	5.9	328	94	72	52	19	8.2	0.71B	0.08
		2021	6.3	542	191	85	72	19	5.7	1.02A	0.10
	LM2	2019	6.7	373	82	32	63	11	2.4	0.56B	0.06
		2020	6.6	404	77	32	56	9	2.6	0.71B	0.07
		2021	6.6	477	183	60	68	16	6.3	0.87A	0.09
5-15	LM3	2019	6.5	419	95	19	68	12	2.1	0.57	0.06
		2020	6.0	284	81	38	38	12	2.1	0.57	0.06
		2021	6.2	377	109	30	47	13	2.6	0.53	0.06
	LM2	2019	6.6	324	94	14	46	7	1.1	0.41	0.04
		2020	6.8	410	111	32	62	9	2.6	0.46	0.06
		2021	6.2	319	76	31	45	12	2.6	0.49	0.05
15-30	LM3	2019	6.5	404	88	10	68	7	1.4	0.40	0.04
		2020	6.4	322	87	18	51	7	1.1	0.35	0.04
		2021	6.4	363	83	14	56	9	1.8	0.35	0.04
	LM2	2019	6.5	345	66	9	57	5	0.9	0.35	0.03
		2020	6.6	336	96	16	55	5	1.4	0.34	0.04
		2021	6.3	292	61	19	42	8	1.4	0.34	0.04

† Indicates significant difference (α=0.1) between treatments and years with depths analyzed separately with uppercase letters

Table 3.5. ANOVA table for three years in pecan orchard with two different soils for comparisons of bulk density (ρ_b), volumetric available water content (AWC), volumetric field capacity (FC), volumetric wilting point (WP), soil porosity (Porosity), and infiltration rate (IR). Measurements at the surface (IR) or 0 to 30 cm (ρ_b, AWC, Porosity) that was split by 0-5, 5-15, and 15-30 cm. The soil differences of one at a higher soil moisture (P1) and one at a lower soil moisture (P3) when considered soil moisture throughout the year when not modified by irrigation.

Coefficients	DF	ρ_b	AWC	FC	WP	Porosity	IR
Year (Y)	2	**	*	NS	NS	NS	*
Soil (S)	1	NS	**	**	**	NS	**
Depth (D)	2	**	NS	NS	NS	**	-
Y x S	2	NS	NS	NS	NS	NS	NS
Y x D	4	NS	NS	NS	NS	NS	-
S x D	2	*	NS	NS	NS	NS	-

** Significant at $\alpha = 0.05$

* Significant at $\alpha = 0.1$

Table 3.6. Mehlich 1 extractable nutrients, and calculated water soil pH from calcium chloride measured by years for Pecan orchard with two locations within for comparisons at a depth of 0-5 cm. The treatments with higher soil moisture movement dynamics (P1), and lower soil moisture movement dynamics (P3).

Depth	Treatment	Year	Mehlich 1 Nutrient								
			pH	Ca	K	P	Mg	Mn	Zn	TOC	TON
cm				----------------mg kg^{-1} -------------						----%----	
0-5	P1	2021	6.4	1,224	109	90	182	31	15.6	1.91	0.13
		2022	6.3	1,605	103	75	353	23	23.1	2.01	0.13
		2023	6.6	1,427	169	94	268	15	21.1	2.42	0.17
	P3	2021	6.7	1,224	115	124	104	33	15.1	1.64	0.12
		2022	6.8	2,251	127	131	545	28	24.5	2.00	0.14
		2023	6.6	1,593	136	134	278	16	24.9	2.07	0.15
5-15	P1	2021	5.3	546	37	15	86	17	1.9	1.47	0.07
		2022	5.8	680	33	21	90	14	3.5	1.16	0.06
		2023	5.8	562	45	13	89	8	2.3	1.25	0.06
	P3	2021	6.3	576	21	21	23	13	1.5	0.98	0.05
		2022	6.0	647	31	26	44	11	1.8	0.94	0.04
		2023	6.1	520	28	27	49	7	3.3	0.91	0.04
15-30	P1	2021	4.9	213	27	9	47	9	0.9	1.13	0.06
		2022	5.1	419	27	18	62	11	1.7	0.86	0.05
		2023	5.0	198	16	6	41	4	0.6	0.89	0.04
	P3	2021	5.7	260	23	7	21	11	0.4	0.47	0.03
		2022	5.5	265	26	10	26	11	0.5	0.57	0.03
		2023	5.7	223	17	8	19	5	0.3	0.49	0.02

Table 3.7. Bulk density (ρ_b), water stable aggregates (WSA), volumetric available water content (AWC), volumetric field capacity (FC), volumetric wilting point (WP), soil porosity (Porosity), and infiltration rate (IR) measurements for three years in pecan orchard systems with two different soils within location for comparisons. Measurements at the surface (IR) or 0 to 30 cm (ρ_b, WSA, AWC, FC, WP, Porosity). The soils varied by higher soil moisture (P1) and lower soil moisture (P3) when considered soil moisture throughout the year when not modified by irrigation.

Depth	Treatment	Year	ρ_b	WSA	AWC	FC	WP	Porosity	IR
			g cm^{-3}	%	---cm^3 cm^{-3}---			%	cm h^{-1}
0-5	P1	2021	1.21	91	0.14	0.21	0.07	47	26
		2022	1.14	73	0.15	0.16	0.06	47	20
		2023	1.17	70	0.16	0.18	0.06	52	6†
	P3	2021	1.16	94	0.10	0.16	0.06	49	35
		2022	1.17	79	0.11	0.18	0.06	45	28
		2023	1.12	75	0.18	0.12	0.06	50	22
5-15	P1	2021	1.44	91	0.14	0.20	0.07	44	-
		2022	1.60	87	0.14	0.21	0.07	41	-
		2023	1.37	59	0.16	0.17	0.06	39	-
	P3	2021	1.34	89	0.11	0.16	0.05	46	-
		2022	1.27	86	0.11	0.15	0.04	41	-
		2023	1.45	84	0.08	0.13	0.05	37	-
15-30	P1	2021	1.31	-	0.10	0.14	0.06	42	-
		2022	1.18	-	0.13	0.17	0.05	39	-
		2023	1.54	-	0.16	0.22	0.06	39	-
	P3	2021	1.48	-	0.06	0.12	0.06	41	-
		2022	1.43	-	0.12	0.13	0.04	38	-
		2023	1.52	-	0.10	0.15	0.05	38	-

†soil saturated

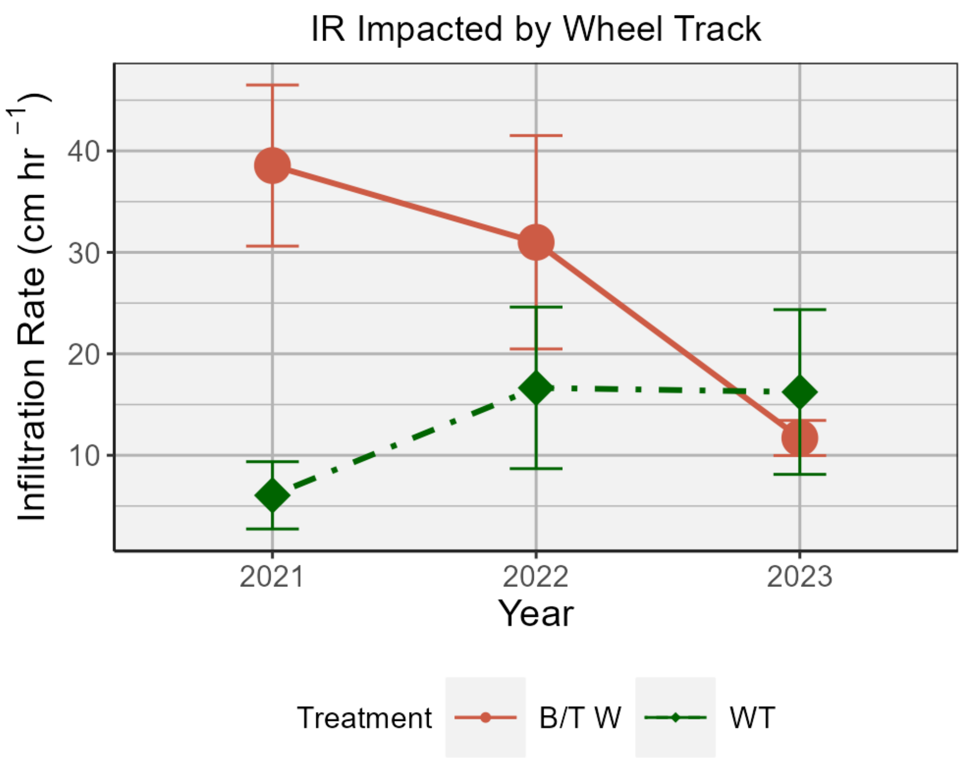

Figure 3.1. Infiltration rate impacted by tractor wheel tracks (WT) versus between wheel tracks (B/T W) over time at the pecan site. Greatest difference in infiltration was in 2021 between the wheel tracks compared to wheel track area ($\alpha = 0.1$).

CHAPTER 4

PEDOTRANSFER FUNCTIONS TO ESTIMATE SOIL HYDRAULIC PROPERTIES FOR SOME GEORGIA SOILS

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Abstract

Soil hydraulic properties like water content and infiltration rate are important for a variety of applications including watershed modeling and irrigation management. Measurement of these properties is often time-consuming and cost prohibitive. Pedotransfer functions (PTFs) can be valuable tools for estimating hard-to-measure properties because they utilize physical and chemical soil properties that are more readily available to predict soil hydraulic properties in lieu of direct measurements. Many of these on-farm management choices use prediction models but are based on more generalized geography-based data. Our overarching focus was to compare measured values of some soil hydraulic properties from two physiographic regions in Georgia to estimates from commonly-used PTFs developed from large national-scale databases and localized models. Properties of interest included water content at field capacity (0.03 MPa; FC) and wilting point (1.5 MPa; WP), available water content (AWC), and saturated hydraulic conductivity (Ksat). Data from 191 undisturbed soil cores were combined with measured soil texture, bulk density, total organic carbon (TOC), and depth from co-located samples to develop linear regression models for hydraulic properties (GA models) and as input and validation for the Rosetta3 and Saxton and Rawls (2006) PTFs. Soil texture coefficients had the largest relative importance in GA models for FC and WP at >69% while TOC was 70% for the AWC model. The GA models had better model performance for FC, WP, and AWC than the more generalized Rosetta3 and Saxton and Rawls (2006) models when analyzed on GA soils. The best performing model was the GA model for WP with an RMSE of 2.17 compared to RMSEs of 8.78 and 12.82 for Rosetta3 and Saxton and Rawls (2006) models, respectively. This is likely a result of using only GA soils to describe property relationships in the GA models whereas the generalized models were developed with a diverse set of independent soil information. Both the GA model

and the Saxton and Rawls (2006) equations generally underpredicted the measured Ksat values and had RMSEs of 7.5 and 11.4, respectively. All GA models that were developed were less intensive to sample and specifically representative of Georgia soil characteristics from some Piedmont and Coastal Plain soils. This study demonstrates the need for having localized models to predict soil hydraulic parameters to support practical applications for producers and site planners in Georgia while quantifies some potential errors from using more geographically generalized models.

Introduction

Estimates of soil hydraulic properties are necessary for numerous hydrologic and agronomic applications such as watershed modeling and irrigation management. Water content and conductivity measurements require specialized equipment to collect and analyze samples. Consequently, these measurements are costly and often require more time to complete than routine analysis like, nutrients, texture, carbon, and bulk density. The most common way to bridge the gap between measured values and estimates has been with pedotransfer function (PTF) models (Schaap et al., 2001; Saxton & Rawls 2006; Zhang & Schaap, 2017). These models are often developed from large databases with data from local to continental scale scales. Many of these well-known models are often the first choice for applications in agronomic or hydrologic models like DayCent, the Soil Water Assessment Tool, TOPMODEL, Agricultural Pro-duction System simulator (APSIM), and many others (Bagnall et al., 2022) when measured values are not available.

Managing soil moisture for crop production requires knowledge of water storage capacity and infiltration rates of soils at the field scale. In 2017, >63% of the harvested acres in Georgia were irrigated (NASS, 2017). One of the most important factors to consider for water storage capacity is the soil water retention curve (SWRC) which represents the hydraulic function of a particular soil often based on water content at field capacity (FC) and the wilting point (WP). The difference in values between these two points can be used to estimate the available water content (AWC) to plants which can subsequently be used to inform irrigation decisions. Collecting information to create the SWRC can be very time-consuming and costly. This combined with limited options for submitting samples to be analyzed by commercial soil labs often leads to estimating these properties with models. One of the most common ways to estimate hydraulic properties like FC and WP is with PTFs (Bagnall et al., 2022; Saxton & Rawls, 2006; Schaap et al., 2001; Zhang & Schaap, 2017. These models utilize physical and chemical soil properties that are more readily available to predict soil hydraulic properties in lieu of direct measurements.

There are many PTF models available that predict hydraulic properties across a range of geographic extents and soils using a variety of simple and complex models (Patil & Singh, 2016). One of the most widely adopted models to describe water retention parameters is the van Genuchten equation (1980) which describes the relationships between hydraulic properties at specific points along the SWRC. In the van Genuchten model, limited information of soil texture and water content can be used to approximate water content at a specific point. Rosetta software can be used with additional information of particle size and bulk density used for refining the model more tailored to site-specific (An et al., 2021). Rosetta is a PTF that predicts hydraulic properties using the van Genuchten water retention parameters (Schaap et al., 2001). Since the creation of the Rosetta1 model there have been updates with the optimization of van Genuchten model parameters weight in the Rosetta model to make Rosetta3 (Zhang & Schaap, 2017). Another common model is a suite of regression equations developed by Saxton and Rawls (2006). One primary difference in Saxton and Rawls (2006) equations is the addition of soil C to improve predictions. The availability of soil texture and organic matter information in agronomic systems makes the potential applications of PTFs a real possibility and is especially relevant for areas with extensive irrigation. Furthermore, many management practices are geared toward increasing soil organic matter which PTFs that include that as a predictor may be especially important.

Increased soil organic C has been observed in connection with increased soil structure and greater aggregation. These improvements can lead to better water movement into and through the soil (Chalise et al., 2019; Rankoth et al., 2021). Soil aggregation has a strong relationship with carbon and can be used improve predictions of hydraulic parameters (Liu et al., 2005; Steele et al., 2012). Intact cores require more effort to obtain, but disturbed cores lack the natural soil structure, which can result in a loss of information on how the water dynamics are changing in situ (Bagnall et al., 2022). One method used by farmers to reduce compaction is planting cover crops, which also adds C to the soil and can lead to improved water movement into the soil, (Hubbard et al., 2013). Tillage can quickly change soil structure and reduce organic matter (Blanco-Canqui et al., 2022) and cover crops take time to reestablish a more natural structure free of compaction from agricultural activities. In the soil surface, cover crops and their resulting residue prevent the destruction of soil aggregates by keeping the ground covered (Chalise et al., 2019). Furthermore, soil crusting from rain events can be reduced by using cover crops, which allows for better water movement into the soil and can affect the amount of water in the soil available to plants (Chalise et al., 2019). Improvements from cover crops take time, but benefits in aggregate stability can be realized as short as one year after implementing some practices (Acuña & Villamil, 2014). Cover crops can improve hydraulic parameters, water holding capacity, and subsurface recharge (Hubbard et al., 2013; Rankoth et al., 2021) which are important for soil health and useful when measurements are not possible (Bagnall et al., 2022).

Models that take into account geographic location have also been used to predict soil properties to account for inherent location variability to reduce error in predictions (Ramcharan et al., 2017). An issue some have had with regional pedotransfer functions is the lack of ability to apply to larger geographic regions, limiting the use of the models (Gijsman et al., 2002). The opposite is also true, which means that more general models may result in larger prediction errors when applied to specific regions or smaller geographic areas. For this reason, it is likely that location-specific PTFs will be necessary until generic models like Rosetta are further refined and validated (Patil & Singh, 2016). While arguments could be made for choosing one model over the other, minimizing prediction error is critical for producers when crop production decisions need to be made for economic reasons and water use efficiency.

This research aims to develop PTFs specific to Georgia soils to estimate the hard-to-measure hydraulic properties (FC, WP, AWC, and saturated hydraulic conductivity) from relatively easier-to-measure soil physical and chemical properties. Another objective was to compare the localized models to Rosetta3 and the Saxton and Rawls (2006) models to evaluate national and international model performance with local models for soils collected in two regions of Georgia. Our hypothesis was that localized models would outperform the national-scale models when analyzed on GA soils.

Materials and Methods

Sampling methods

Soils representing three crop fields in Georgia's Piedmont and Coastal Plain physiographic regions were collected from 2019-2023. The Georgia Piedmont site was located near Watkinsville, GA and the Coastal Plain sites were located near Stapleton, GA, and Midville, GA. At each sampling location, undisturbed soil cores were taken from three depths (0-6, 9-15, and 19-25 cm) concurrently with additional collections of bulk density and composite samples in a variety of corn, cotton, and pecan treatments. A total of 191 undisturbed soil cores representing three depth increments were collected and analyzed for volumetric water content at field capacity (0.033 MPa; FC) and the permanent wilting point (1.5 MPa; WP). Soil cores were 6 cm high and had a diameter of 5.35 cm. Cores were wrapped with plastic wrap and refrigerated until being analyzed for FC. The cores were wetted to saturation from the bottom up and then placed in the Tempe cell until cores were at saturated field capacity (SoilMoisture Equipment Corp., Santa Barbara, CA, user manual). Following FC measurement, soils from each core were air dried and a 20-g subsample was used for oven-dry correction. Water content at the WP was determined using a ~5g subsample from the air-dried core samples with a WP4C Dewpoint Potential Meter (Meter Group, Inc. USA, user manual). AWC was calculated from the difference between FC and WP.

Additional measurements were obtained from composite soil samples taken from the same three depth increments represented by the undisturbed cores (0-5, 5-15, and 15-30 cm) using a 2-cm diameter push probe with ~10 samples distributed around each cluster of undisturbed cores. Composite samples were air-dried and sieved through a 2-mm sieve for subsequent analysis. An 8 g subsample was ball-milled and prepared for analysis of total organic carbon (TOC) by dry combustion (Bremner, 1996). Particle size analysis was determined with a Laser Particle Size Analyzer (LPSA, Beckman Coulter LS 13 320, Indianapolis, IN). Duplicate 0.5 g subsamples of the 2-mm sieved soil were weighed into 15-ml centrifuge tubes and mixed with 5 ml of sodium hexametaphosphate (50 g L^{-1}) before shaking overnight on a horizontal shaker. Samples were then transferred to 13-ml test tubes for analysis by laser diffraction. Water stable aggregates (WSA) were measured with an Eijkelkamp 8.13 wet sieving apparatus (Eijkelkamp Soil & Water, Giesbeek, Netherlands) with the provided procedure with samples taken from composites that were used in texture analysis from each point (Kemper & Rosenau, 1986). Bulk density was calculated from a core adjacent to the Tempe cells at each location. Approximately 155 samples of the bulk density samples were collected with a single core 8.5-cm diameter by 6-cm depth and the remaining samples taken using a slide hammer with a multi-stage section sleeve 5.08 cm diameter and separated by the same depth splits same as composites (0-5, 5-15, and 15-30 cm).

Soil hydraulic conductivity was measured at the soil surface using a SATURO dual head infiltrometer (METER Group, Inc. USA). A 16-cm diameter ring was inserted into the soil surface 10 cm, and the SATURO was secured to the top of the ring prior to analysis. A total of 52 measurements of SATURO were taken from a field in a Cecil soil map unit located near Watkinsville, GA over four years and had one K_{sat} measurement paired to one undisturbed soil core.

Pedotransfer Function Models

Two existing pedotransfer function models were used to predict FC, WP, AWC, and K_{sat} using combinations of sand, silt, clay, organic matter, and bulk density to evaluate model performance for the samples collected at the sites described above. The first model evaluated was the Rosetta PTF (Rosetta3) developed using a database of 2,134 soil samples from North America and Europe (Schaap et al., 2001; Zhang & Schaap, 2017). It can predict volumetric water content at specified points along the water retention curve using a variety of input data. Version 3 of the model was implemented in R from the soilDB package using sand, silt, clay, and bulk density (Zhang & Schaap, 2017). The second model evaluated was the collection published by Saxton and Rawls (2006), which included equations for a wide range of hydraulic soil properties. They were developed with samples from the USDA/NRCS National Soil Characterization database representing approximately 4,000 samples split between A-horizon and B-C horizons using linear regression. This study implemented predictions for FC, WP, AWC, and Ksat using equations developed by Saxton and Rawls (2006) using sand, silt, clay, and TOC and assuming a density factor of 1 and gravel impact of 0 (code from https://github.com/ldemaz/rcropmod).

In addition to using the existing Rosetta and Saxton and Rawls models, stepwise linear regression was run using simultaneous forward and backward model to predict measured values of FC, WP, AWC, and Ksat using the step AIC function in the MASS package (Venables & Ripley, 2002). Inputs to the models included clay, sand, BD, TOC, water-stable aggregates, and sample depth. In addition to developing an independent regression model for AWC, it was also estimated by taking the difference between the predicted values of FC and WP from their respective regressions (subtracted AWC). The final models were used to predict values for each respective property, hereafter referred to as the GA models. Each measured value was compared to predicted values from the three different models for the three different soil water parameters using the root mean square error (RMSE) and Coefficient of Determination (R^2). The relative importance of variables in the final model of GA models was determined using the relaimpo package in R with the lmg method which does an R^2 for each of the coefficients separately by averaging over orderings that gives the output for coefficients with the greatest relative importance in the linear model (Groemping, 2006; Kruskal, 1987). All models were developed in R studio version 2023.12.1 using R version 4.3.3 (R Core Team, 2021).

Results and Discussion

Summary of Measured Data

Soil data used to evaluate existing PTF models and develop new predictions represented a diverse set of Georgia samples from the Piedmont and Coastal Plain physiographic regions. The 155 soil samples from the Piedmont represented loam, clay loam, and clay texture classes with a TOC range of 0.29 to 1.97 % (Table 4.1). The 36 samples from the Coastal Plain were predominately sandy loam textures with some sandy clay loams and a TOC range from 0.34 to 2.42 % (Table 4.1). The three sites had variations of texture and TOC by depth and location which were the parameters used in the GA models (equations 4.1-4.3). Measured parameters of water retention ranged from a minimum 2.2% for a WP sample to 40% for a FC sample and a maximum AWC of 37.8% for all the 191 data points (Table 4.1). Measured bulk density values ranged from 1.12 to 1.85 g cm^{-3} (Table 4.1). K_{sat} used for the final model had a range of 35.98 cm hr^{-1} and a median of 8.63 cm hr^{-1} for the 52 samples used to make the model as they were only surface measurements.

Water Retention Predictions

Model fit for the 191 measured values of water content in this study was low for all three models tested as indicated by RMSE and R^2 (Table 4.2). Models of WP had the strongest relationships between the measured and predicted values from all three methods (Table 4.2). The GA model explained more variability in the data than Rosetta or, Saxton and Rawls (2006) equations. Our GA model for FC was the simplest with just clay and TOC as predictors (Eq. 4.1). The GA model for WP was the only one that included depth as a predictor (Eq. 4.2). Both the WP and AWC GA models included three variables (Eq. 4.3).

$$\text{GA model FC} = (0.1583 * \text{clay}) + (4.3375 * \text{TOC}) + 9.0123 \qquad \text{(Eq. 4.1)}$$

$$\text{GA model WP} = (0.04004 * \text{silt}) + (0.10338 * \text{clay}) + (-0.07465 * \text{depth}) + 3.8269 \qquad \text{(Eq. 4.2)}$$

$$\text{GA model AWC} = (3.85722 * \text{TOC}) + (0.13314 * \text{clay}) + (0.05898 * \text{sand}) + 1.1138 \qquad \text{(Eq. 4.3)}$$

The GA model for WP had the lowest RMSE and largest R^2 value of any of the models evaluated for the 191 measured GA samples (Table 4.2). One reason for less variability in GA model WP was that TOC was not a coefficient selected in the final stepwise regression model. This may have been influenced by TOC controls on FC that are more pronounced than for WP (Bauer & Black, 1992). While TOC is more influential in FC than WP, both water retention measurements have a greater influence from soil texture than TOC (Bauer & Black, 1992). The RMSE for AWC models was lower for all models compared to FC but not as low as WP models. This may reflect the combined lower variability in WP and the greater variability in FC having a predictable RMSE value between FC and WP for AWC (Table 4.2). Similar to Bagnall et al. (2022), the GA model had the largest RMSE for the FC model and smallest in WP model. Saxton and Rawls (2006) model for 1,797 samples from the National Cooperative Soil Survey, had less RMSE variation between the FC and WP than Bagnall et al. (2022) reported with the same data set analyzed from their model based on 124 long-term sites. The limited improved performance of the Bagnall et al. (2022) model compared to Saxton and Rawls model on national databases displays the difficulty of improving models for large geographic scale with few predictors. Using samples from the National Cooperative Soil Survey, the models of Bagnall et al. (2022) performed better than Saxton and Rawls on 5 of the 15 models for the same five soil texture classes sampled in GA to predict the FC, WP, and AWC. Creation of new models don't always perform better than older ones. For example, the Bagnall et al. (2022) model outperformed Saxton and Rawls (2006) on non-calcareous soils 42% of the time across the twelve soil texture classes and three hydraulic parameters predicted and 25% of the time better for calcareous soils (Bagnall et al., 2022). The soils in GA were not calcareous, but the focus on regional issues like calcareous soils impacting model performance supports the need for regional models. Running the Saxton and Rawls (2006) model on the GA measured data set compared to the GA model had greater variation between the FC and WP and larger overall RMSE value compared to the GA model. The Bagnall et al. (2022) model didn't always outperform Saxton and Rawls's (2006) on different texture classes, but both identified soil organic carbon as a sensitive indicator which suggests the importance of organic matter as a predictor for water retention. Having non-geographic specific models to allow for application in locations where models are not developed was the purpose of models like Rosetta3 and Saxton and Rawls (2006) as this limits the area the model can be used. While this has a use including location can also be an important predictor as used in another PTF for bulk density, the importance of C was still present, but the next most important factor was the location from a state/providence geographic level (Ramcharan et al., 2017). While the two models compared to the GA models don't use location, other models finding a strong relationship highlights how geographic variability can impact models. The addition of location can create a limitation in using data from a local level, reducing the amount of data used to create the model. Reduction in sample size for model building reduces the variability the model accounts for in the coefficients, making it less robust in different scenarios. Utilization of a large data set determined by the modeler can be so large as to cover all the variability that would occur from location to location, while less precision per sub-geographic region can potentially perform better on a larger geographic scale.

One way to explore model performance is by evaluating variable importance. Clay was the most influential coefficient in WP and FC models (> 69% relative importance), whereas TOC was more important in the AWC model with (70% relative importance). Clay was important in the GA models for FC and WP, as it effectively differentiated the two regions from which soils were taken (Piedmont and Coastal Plain). This is analogous to the findings of Ramcharan et al. (2017) and Patil and Singh (2016) who both reported the importance of location for PTF performance.

An important caveat about the GA models is that the reported RMSE and R2 values are based on all of the data used in this study. These metrics describe the amount of variability explained by the independent variables whereas the Rosetta and Saxton & Rawls (2006) models were developed on completely different sets of data. Our comparison presents the best possible scenario for explaining data from our study.

Saturated Hydraulic Conductivity Predictions

Saxton and Rawls (2006) also provide a way to estimate the K_{sat} using sand, clay, and TOC. The model had fewer coefficients than the GA model, which had sand, TOC, bulk density, and volumetric water content at sampling time (Eq. 4.4). This only added one additional sample taken compared to the Saxton and Rawls's (2006) model which requires bulk density and volumetric water content taken at the time of sampling. The additional sample may add time and cost to measurements, but all of the data used in this comparison for 52 samples were from surface to 6 cm at the deepest depth from the soil surface using a bulk density core. The GA model had a lower RMSE and higher R^2 compared to the predictions with the Saxton and Rawls (2006) equation (Table 4.3). In the paper, Saxton and Rawls (2006) had the performance of different models for K_{sat} measured vs. predicted based on other previously developed models, with the final model used explained by how it works relative to other influential properties in the model. Also, the method for obtaining K_{sat} values varied as SATURO system being used in GA model versus another method of data collection used in Saxton and Rawls (2006). Bulk density (40%) and volumetric water content at the time of sampling (34%) were the most important variables for predicting Ksat with the GA model and the remaining 26% of model performance was split evenly between TOC and sand. Compaction influences the K_{sat} value at the time of measurement from water movement into the which clay soils also have a lower water movement into the soil generally as the same result of water issues moving into the soil (Blanco-Canqui et al., 2002; Bouma, 1980). The benefit of using these models is that they provide a way to estimate the K_{sat} as opposed to measuring it with a special device like the SATURO method used in this study, which had an average run time in the field of 74 minutes to collect one data point. To collect enough data points to represent an area that accounts for variability in locations would be time-consuming, and increasing the amount of the automated running equipment of SATURO, which has a high cost when considering time and equipment cost, leads to the need for improved time efficiency.

$$\text{GA model } K_{sat} = (0.1859 * \text{sand}) = (-16.1553 * \text{BD}) + (8.7799 * \text{TOC}) + (-0.2007 * \text{volumetric water content}) + 21.1354 \quad \text{(Eq. 4.4)}$$

Model Parameter Differences

To compare model differences, our model for FC had two variables to make predictions of clay and TOC (Eq. 4.1). This model for FC was similar to the Saxton and Rawls (2006) model which included TOC, clay, and sand as parameters to predict the FC. The Rosetta model does not account for TOC but used texture parameters and bulk density. For the WP, the GA model used the same parameters as Saxton and Rawls (2006) and Rosetta as they were for FC in their models. The model determined here for WP included silt, clay, and depth. The Rosetta model has the same determination method with parameters for FC being 0.03 MPa and 1.5 MPa for WP, then mathematically subtraction WP from FC. Saxton and Rawls (2006) are similar but account for density factor and gravel, but use with this sample set had a density factor of 1, which is the default, and a gravel factor of 0. These impacts from gravel and density created no differences in our AWC value.

The creation of a PTF on a local scale could have benefited from more site-specific data to better represent variability reflected in national and multi-continental scale models. Similar to the Saxton and Rawls (2006) and Rosetta models, soil texture information strongly influenced the GA models. The GA model was made from Piedmont (n = 155) and Coastal Plain (n = 36) soil. The split with texture with sandy loam and sandy clay loam for Coastal Plain soil and Piedmont soil increasing with clay by depth going from loam, clay loam, and clay in the 15-30 cm depth. The creation of the Rosetta and Saxton and Rawls (2006) was made with a large database as covered in the methods of this paper and soil texture class as compared to the GA model using a lot of loam to clay loam plus increasing sand and clay to go to other texture classes. Texture class impacting the model has been explored for Saxton and Rawls (2006) model compared by Bagnall et al. (2022) who also had a model using 1,797 soil samples from A to C horizons from the National Cooperative Soil Survey Characterization database. The comparisons between the two models were run separately by texture class by Bagnall et al. (2022) using RMSE to compare predicted vs. actual, which had a range of RMSEs from 2.1 to 14.0 for the different texture classes for models of WP, FC, and AWC. Other studies comparing models with large data sets to large data sets had a range of RMSE that was similar to the GA model on GA soils. GA model compared to Saxton and Rawls (2006) had TOC being an influential factor but different in the bulk density not being impactful as used in the Rosetta model selected. All models discussed here had one main item in common with data needed to make predictions had few coefficients needed to be collected from different sampling methods. Not surprisingly, soil texture is critical for PTF models but recent research has suggested the need for adding soil C or organic matter to improve predictions (Bagnall et al., 2022; Nemes et al., 2003; Patil & Singh 2016; Saxton & Rawls, 2006). As sampled for GA model, the soil collected from the push probe composite samples can be analyzed for texture and TOC. The push probe reduces the need for only one piece of specialized equipment and access to a soil testing lab for samples to be analyzed for texture and TOC is more practical than finding a lab to measure FC and WP.

Conclusions

The GA model for FC, WP, and AWC had better performance than Rosetta3 and Saxton and Rawls (2006) models likely due its localized nature. The GA models explained variations in hydrologic properties using texture, TOC, and sampling depth as coefficients which keeps the sampling equipment needed to a minimum. The ability to composite the samples creates an opportunity to cover a large area with fewer samples submitted to the soil lab for analysis, making it more practical than the alternative of FC and WP measurements taken at a single point. The FC and WP also take more time and specialized equipment to collect and analyze than inputs to the PTF models. Producers needing samples analyzed for AWC from FC and WP measurements have very limited locations in GA to submit samples for analysis, decreasing the practicality of measuring these properties. Outside the state of Georgia within the US there are few labs measuring these properties which limits options for estimating these important parameters. K_{sat} measurements from SATURO require significant time commitments and specialized equipment, which can be costly, to measure in-field, but estimations from modeling can become more practical. The utilization of surface soil samples that use the same sampling methodology for FC and WP just needs the additional bulk density and volumetric water content at the time of sampling from the bulk density ring to estimate K_{sat}, which is advantageous for producers to know with limited additions needed. Interpretation of estimated hydraulic properties from PTFs can vary significantly depending on the models employed and localized models may provide more realistic estimates than those developed for more diverse environments.

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Table 4.1. Summary statistics for measured soil properties of 191 samples used to make GA models and test all model performance. Physical data of texture including sand, silt, clay, and bulk density (ρ_b). Soil chemical data of total organic carbon (TOC). Soil hydraulic data of field capacity (FC), wilting point (WP), available water content (AWC), and saturated hydraulic conductivity (K_{sat}).

Location	Sand	Silt	Clay	TOC	FC	WP	AWC	ρ_b	K_{sat}
	---------------------------- % ----------------------------							g cm^{-3}	cm hr^{-1}
Min	9	12	4	0.29	0.56	2.21	0.62	1.12	1.4†
Max	82	54	70	2.42	39.83	21.46	31.11	1.85	37.3
Median	37	33	26	0.75	17.17	6.85	10.53	1.49	8.6
Range	73	42	65	2.14	39.27	19.25	30.49	0.73	36.0
Std	19	9	16	0.43	5.54	2.63	4.20	0.14	8.4
Ste	1.4	0.7	1.2	0.03	0.40	0.19	0.31	0.01	1.2
ci	2.7	1.3	2.3	0.06	0.79	0.38	0.61	0.02	2.3

†K_{sat} represented 52 samples as it is a surface measurement.

Table 4.2. Model performance of three pedotransfer function models for water content at field capacity (FC) and the permanent wilting point (WP) and available water content (AWC) for 191 samples from the Piedmont and Coastal Plain regions in Georgia.

Property	Model	RMSE	R^2
Field Capacity	Rosetta	13.18	0.08
	Saxton and Rawls (2006)	15.76	0.09
	GA model	5.05	0.17
Wilting Point	Rosetta	8.78	0.26
	Saxton and Rawls (2006)	12.82	0.25
	GA model	2.17	0.32
Available Water Content	Rosetta	5.55	0.002
	Saxton and Rawls (2006)	4.88	0.003
	GA model	3.97	0.10
	GA subtracted FC-WP	4.03	0.10

Table 4.3. Model performance of two pedotransfer function models for saturated hydraulic conductivity (Ksat) for 52 samples from the Georgia Piedmont.

Property	Model	RMSE	R^2
Ksat	Saxton and Rawls (2006)	11.4	0.06
	GA model	7.5	0.18

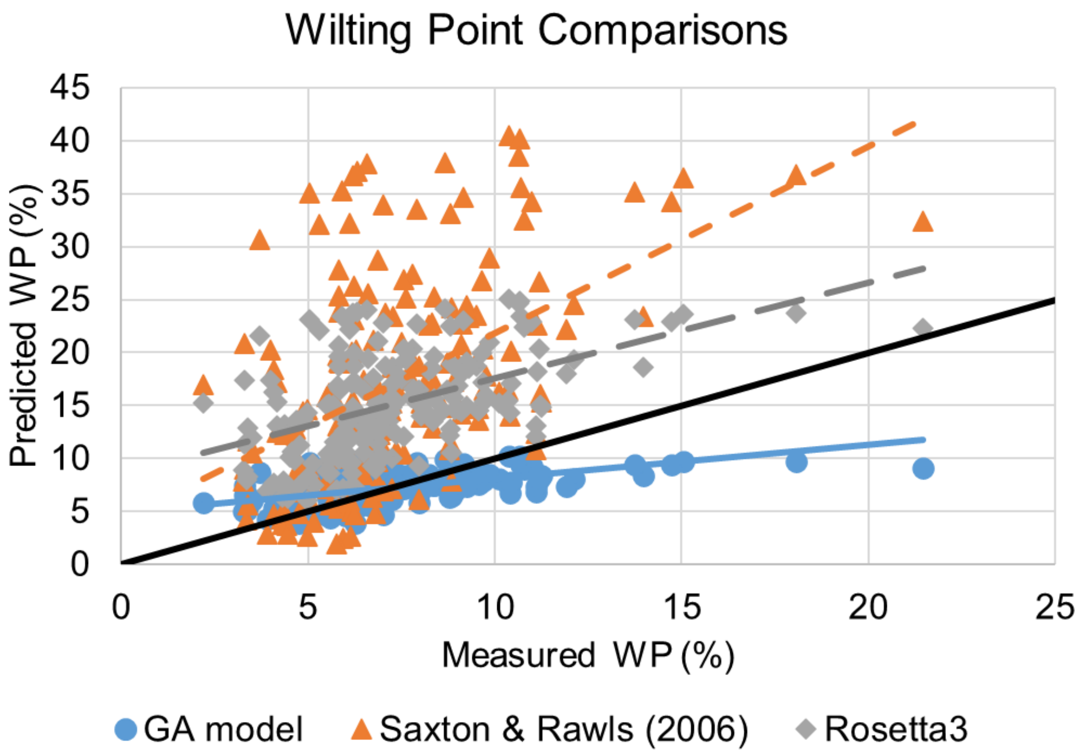

Figure 4.1. Wilting point comparisons between measured and predicted values for GA model, Saxton & Rawls (2006), and Rosetta3 model functions. The black line is a reference 1:1 line.

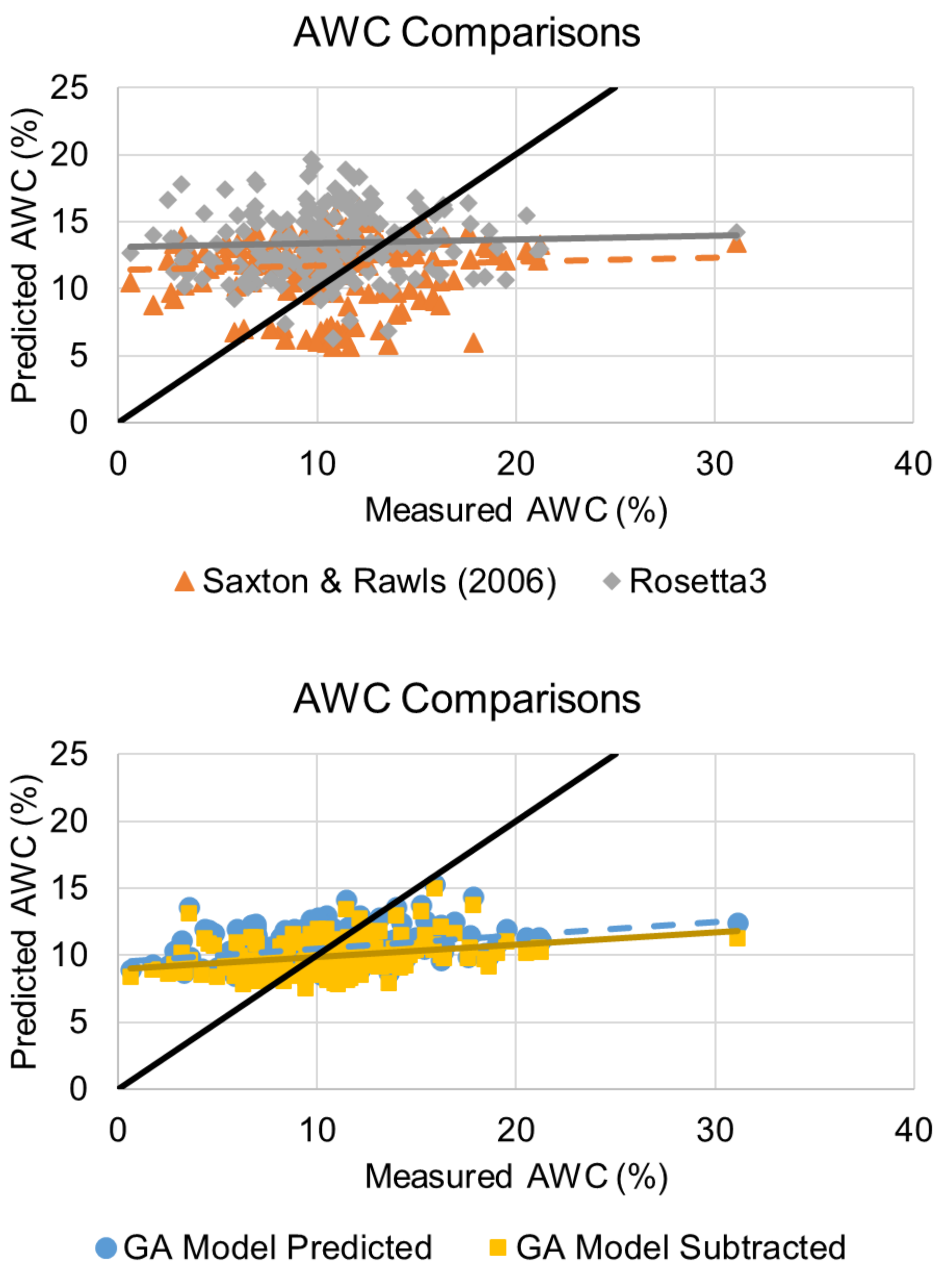

Figure 4.2. Available water content (AWC) comparisons between measured and predicted values for (top panel) Saxton & Rawls (2006), and Rosetta3 model functions and (bottom panel) GA model as predicted and GA model subtracted being field capacity minus milting point. The black line is a reference 1:1 line.

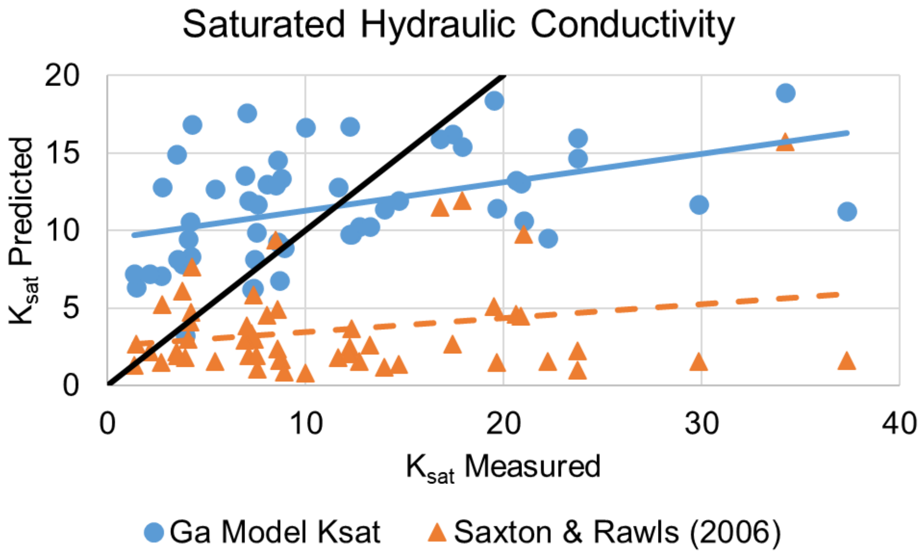

Figure 4.3. Saturated hydraulic conductivity comparisons between measured and predicted values for GA model and Saxton & Rawls (2006) model functions. The black line is a reference 1:1 line.

CHAPTER 5

MACRO- AND MICRO-NUTRIENT POOLS INFLUENCED BY WHITE CLOVER COVER CROP IN A GEORGIA PIEDMONT COTTON PRODUCTION SYSTEM

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Abstract

Cover crop utilization is an important strategy for improving row crop sustainability and critical for managing plant-soil nutrient relations needed to maintain cotton yields in the southeastern United States. Most cover crops are annual species. However, perennial cover crops, sometimes called a 'living mulch' (LM), benefit from working year-round. Living mulch effects on nitrogen and carbon have been explored in corn systems but limited information is available for other nutrients for cotton systems. This project quantified the effect of a white clover LM on nutrient cycling of macro- and micro-nutrients (sans N) in a cotton production system in the Georgia Piedmont. A comprehensive suite of soil, plant, and pore water measurements were collected at important cotton reproductive states for two site years with different soil fertility. Additional samples were taken between cotton growing seasons to evaluate soil-clover interactions. Responses in the system were connected to soil test levels for nutrients at the start of reproduction. When the soil had above optimum K levels (2021), the LM luxury consumed excess K from the soil, whereas this did not occur in the site year with below optimum K (2022). Cotton leaves had the greatest fluctuations in K concentrations when LM was present from pinhead to cutout when soil K was below optimum. In the winter, the soil had the greatest K concentration in treatments with the most clover relative to bare ground. Using optimal LM coverage can prevent excess K from potentially being lost from the system while not affecting cotton leaf K nutrition during reproductive growth.

Key words: Nutrient reservoir, Living Mulch, Potassium

Core ideas:

- Living mulch can luxury consume nutrients like K, which aids in retaining them in the system.

- Soil pore water quantity was reduced in treatments with both living mulch and cotton.
- When an adequate cotton size and yield occurred, LM biomass decreased across reproductive growth stages.
- Living mulch used in K-deficient soils allowed cotton to have a greater K response during reproductive growth

Introduction

In the southeastern United States, cover crops can increase yield, improve soil quality (Nouri et al., 2019), and reduce weed pressure (Weisberger et al., 2023; Weisberger et al. 2024). Despite these benefits, most states in the Southeast have low cover crop use. Only 12% of the cropland planted in Georgia in 2017 utilized cover crops (NASS, 2017). Nevertheless, Georgia has one of the highest rates of cover crop adoption in the southern United States, with more than 50 percent of the 42 producers who responded to a recent survey using cover crops (SARE & CTIC, 2014). Annual species are most commonly used, but the adoption of perennial species as cover crops, sometimes referred to as 'living mulches' (LM), has been explored as a way to further enhance ecosystem services and limit the negative effects of production such as erosion and nutrient loss (De Baets et al., 2011; Hartwig & Ammon 2002; Isse et al., 1999). A growing body of research has evaluated white clover (*Trifolium repens* L.) as a perennial cover crop for southeastern production systems, focusing primarily on soil health and nitrogen (N) dynamics (Andrews et al., 2018; Hill et al., 2021; Peters et al., 2020; Sanders et al., 2017). While N is recognized as a critical nutrient for productivity, other essential macro- and micro-nutrients must be managed properly to maintain adequate yields. Research on the cycling of these macro- and micro-nutrients is lacking for perennial cover crops in similar cropping systems (Andrews et al., 2018; Ginakes et al., 2020; Sanders et al., 2017).

The use of a LM to maintain and release nutrients at key times during the cash crop growing season provides many benefits that can be measured in terms of yield. Nitrogen credits are an obvious benefit from a leguminous LM cover crop, but this system also provides other soil health benefits like increasing soil carbon (C) (Andrews et al., 2018; Hill et al., 2021). As the cash crop canopy shades out the LM, the cover crop dies and decomposes during mid to late summer, releasing nutrients available for uptake by the cash crop (Sanders et al., 2017). The nutrients are available to the cash crop during the growing season but tied up in the cover crop during times when not used by the cash crop. During winter, when the LM is regenerating or any time it is regenerating, it takes up nutrients before they have the potential to be leached out of the system (Sanders et al., 2017). These nutrients are often applied in different forms as fertilizers, like phosphorus (P), which can have a negative effect on the environment if translocated to waterways. The clover cover crop effectively acts as a nutrient reservoir for these macronutrients, due to its perennial function and growth habits.

Improvements in cotton farming with the use of cover crops have many benefits, including the potential to retain and recycle nutrients (Ashworth et al., 2020). In particular, the cycling of nutrients other than N has not been evaluated for cotton production systems with perennial LMs like white clover (*Trifolium repens* L.). Clover has three different primary growth habits (small, intermediate, large), and each has its use, but in the case of cover crops that go through a time of heavy shading out, the intermediate habit is preferred. While the small and large habits rely primarily on either stoloniferous growth (small) or high production seed heads (large), the intermediate habit has the two reproduction methods (Andrae, 2009). The shading of clover that occurs as the canopy of a cash crop expands during the growing season can have an effect similar to animal grazing (reduction in biomass), which requires the clover to regrow for which the intermediate habit is desired. 'Durana' white clover (Bouton et al., 2005), is an intermediate-growth variety that was developed in Georgia largely due to its aggressive ability to spread from high amounts of seed produced with longer flowering periods common in the southeastern US. Additionally, the stoloniferous growth habit is a valuable mechanism for clover to spread (Andrae, 2009). Regrowth is a key factor after the shade-out time from the cash crop. Shading from a corn cash crop in Georgia begins approximately 40 days after planting resulting in clover dying off and contributing nutrient-rich organic matter to the system (Sanders et al., 2017). In cotton, between 7 and 9 weeks after planting, approximately when cotton canopy closure occurs, the use of LM and annually planted cereal rye (*Secale cereale*) has been shown to reduce light interception at the soil surface compared to bareground and crimson clover (*Trifolium* incarnatum; Weisberger et al., 2024). Living mulch used in cotton has been shown to keep the ground covered, but the exact timing of dying off and nutrient dynamics has not been covered. Nitrogen inputs from dying clover is a benefit to the cash crop, but there may be additional nutrients cycled through the LM system. For example, K is highly mobile and has been shown to be taken up in excess by plants when abundant in the system (Bartholomew & Janssen, 1929; Deguchi et al., 2010). Highly mobile nutrients can easily move creating a need for stability in the balance of nutrients needed by the cash crop.

Balancing nutrient availability at key growth stages is critical to support growth and physiological function in cotton production and ensure maximum yield and quality. For example, K is essential for cotton at the reproductive flowering stage due to high plant mobility, the ability to balance charges of anions, and the maintenance of osmotic potential (Oosterhuis, 2002). One study in irrigated cotton showed that more than 50% of essential nutrients were taken up during flowering with P uptake near 75% (Rochester et al., 2012). Potassium is also a key element for cotton fiber development; insufficient K causes lower quality and total yield production (Cassman et al., 1990). The availability of soil P can have various effects on cotton growth, yield, and fiber quality as different varieties can have different responses and tolerances to low P in the soil (Li et al., 2020). Several other nutrients can impact the growth and reproductive potential of cotton. For example, low levels of the micronutrient zinc (Zn) can lower yield and impact physiological processes like protein synthesis (Cakmak et al., 1989). Zinc deficiency symptoms become more prevalent when P levels increase (Cakmak & Marschner, 1987). Adequate available amounts of other nutrients like calcium (Ca) and magnesium (Mg) are also necessary for optimal cotton yield (Kissel & Sonon, 2008).

Given the large proportion of nutrients taken up leading up to flowering of cotton, it can be inferred that fertilizers applied after flowering do not result in a large yield response. Nutrient applications made in season to correct for deficiency must adhere to the principles of proper fertilization. Finding the correct rate to apply nutrients is based on knowing the plant's nutritional status. Petiole testing can be used to assess nutrient status, but leaf tissue samples are more stable and better correlated to yield than petioles (Oosterhuis & Morris, 1979).

To date, most nutrient cycling work conducted using perennial white clover as a LM has focused on corn production systems with an emphasis on N and C (Andrews et al., 2018; Hill et al., 2021; Sanders et al., 2018; Sanders et al., 2017). Cotton research has only recently been incorporated the LM concept (Weisberger et al., 2024), and research on nutrient cycling of macro- and micro-nutrients is lacking. Among other things, corn and cotton have very different nutrient requirements and the key reproductive stages occur at different times of year which do not align the same with perennial white clover responses to day length and temperature (Bryson et al., 2014). Consequently, the ability of the LM to act as a nutrient reservoir likely differs between these two crops. One important difference between an annual cover crop and a perennial LM that may influence the capacity of either to retain nutrients is the method by which they are terminated prior to the establishment of cash crops. Unlike annual cover crops that are completely terminated prior to planting, LMs require the termination of only a portion of the cover crop to allow for seed germination of the cash crop sometimes referred to as a vegetation-free strip (VFS). An optimal VFS width has been identified for corn production in Georgia production systems of 30 cm for some agronomic goals (Sanders et al., 2017), but optimal VFS widths for cotton are still being evaluated (Shome, 2023). Therefore, the overarching focus of this study was to evaluate the influence of varying amounts of white clover living mulch on nutrient cycling in a cotton production system. The objective of this study was to quantify changes in nutrient pools of macro- and micro-nutrients other than nitrogen with different VFS widths in a white clover LM system for cotton production in the Georgia Piedmont. Our primary hypothesis was that treatments with more clover present (thinner VFS) would help retain nutrients and prevent nutrient loss from the available rooting zone. The primary focus was on K, a mobile nutrient and a commonly applied nutrient in cotton production systems.

Materials and Methods

Experimental Design and Site Information

This study was conducted at the J. Phil Campbell Sr. Research and Education Center in Watkinsville, GA (33°52′09.5″ N 83°26'59.8″ W; 219 m elevation). Two single-year cotton trials were evaluated during the 2021 and 2022 growing seasons on spatially adjacent plots. The location of plots was moved to accommodate a change in the irrigation infrastructure constructed between growing seasons. Both sites were established in the fall prior to the growing season by planting white clover (*Trifolium repens* var. 'Durana®') at 9 kg ha^{-1} in 2020 and 3.3 kg ha^{-1} in 2021 (Shome 2023). The lower seeding rate was used to establish the 2022 trial based on little difference in clover stand establishment for the same two seeding rates evaluated the previous year. In both years, cover crops were planted with a no-till drill with a row spacing of 19 cm (www.greatplainsag.com). The soil for both sites was mapped as a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult; (Soil Survey Staff, 2019).

Treatments and Management

Three vegetation-free strip (VFS) treatments were established prior to planting cotton in the spring of each year to represent a wide strip (bare ground with no vegetation equivalent to 90 cm of VFS), medium strip (30 cm of VFS), and narrow strip (0 cm of VFS in 2021 and 15 cm of VFS in 2022). Different VFS width treatments controlled the amount of LM present, which was hypothesized to impact nutrient availability and cycling. The treatments were established in a randomized complete block design with three replications. Two weeks before planting, Glyphosate herbicide (1.26 kg ae/ha) and dicamba herbicides (0.81 kg ae/ha) applied at 280 L/ha were used to establish VFSs using a tractor-mounted drop sprayer with a banding nozzle. Cotton was planted in the center of each VFS using a MaxEmerge2 planter with row cleaners (Deere & Company, One John Deere Place, Moline, Il 61265) and with cotton row spacing at 90 cm for all treatments. Each plot had four rows that were 9.9 m long. The University of Georgia Cotton Production Guide (Hand et al., 2023) was utilized for management decisions, irrigation, and standard nutrient additions for each year. The fertilizer applied to the soil surface for this trial included 67.25 kg ha^{-1} of K (potash) and 22.4 kg ha^{-1} of P (triple super phosphate) near the time of crop planting.

Sampling and Measurements

To capture changes in nutrient pools across each VFS treatment, soil, plant, and pore water samples were taken concurrently at specific cotton phenological stages during the summer of 2021 and 2022. Winter soil and water samples were also collected between the two growing seasons from the 2021 plot locations. Summer sampling was conducted at pinhead square, one week before the first flower, at first flower, one week after the first flower, and cutout. Samples were taken when 50% of the plot reached the respective described phenological growth stage.

Pinhead square is the reproductive growth stage of cotton when the first square is identifiable (Ritchie et al., 2007). First flower is when the first white bloom appears on a cotton plant. Cutout is when flowers no longer develop on a plant at approximately 4 or 5 nodes above the first white flower (Ritchie et al., 2007). Physiologically, the importance of cutout represents the time when carbohydrate supply equals the demand, and the point vegetative growth stops. Reduced growth at cutout prevents additional sites for harvestable fruit set.

Cotton samples were collected during the summer at the growth stages mentioned above by compositing the uppermost fully extended leaf from 15 to 20 plants in each plot. Above-ground clover biomass and nutrient concentration samples were taken using a 0.25-m^2 sampling quadrat from each plot at every sampling time. The quadrat was centered between the cotton rows on the LM strip for each treatment. Biomass and nutrient concentration were used together to estimate the LM's nutrient content. Soil samples from 0-10 cm and 10-30 cm were collected with a push probe (2-cm diameter) by compositing approximately 10 samples per plot separated by depth. These depths were selected with the rationale that 0-10 cm was the zone most likely to be impacted by clover decomposition, and that the 10-30 cm represented the majority of the root zone. A suction lysimeter (1900L, Soilmoisture, www.soilmoisture.com/1900L-Near-Surface-Samplers/) was installed in each plot below the root zone (50 cm) near the cotton planting row in-between plants in the row in each of the three treatments to extract pore water for estimating nutrients leaching below the plant's available rooting depth (Alfaro et al., 2006).

All soil, water, and plant samples (cotton and clover) were analyzed for P, K, Ca, Mg, Zn, and Mn. Soil samples were air-dried and passed through a 2-mm sieve, then analyzed for Mehlich-1 extractable nutrients on an inductively coupled plasma spectrometer (Kissel & Sonon, 2008). Water content of air-dried samples was determined at 105°C to express results on an oven-dry basis. Soil pH was measured using a 1:1 soil to 0.01 M $CaCl_2$ and a standard value of 0.6 was added to approximate a 1:1 soil-to-water pH (Kissel & Sonon, 2008). Plant samples were dried at 65ºC until a consistent weight was reached and then sieved to pass a 1-mm sieve before digestion with HNO_3 and H_2O_2, then analyzed by ICP-OES (Jones & Case, 1990). Water samples from summer sampling were filtered through Whatman 42 filter paper and analyzed for all times in which field samples could be obtained using ICP-OES (EPA, 1994). Winter samples were combined between the two sample months to ensure adequate sample sizes for analysis but remained separated by replication and treatment. All water samples were frozen until preparation for analysis. Yield data was combined as the sum of the hand harvest for the subplot area and machine harvest (Case 1822 two-row spindle picker, 2701 Oakes Road Sturtevant, WI 53177) for the remainder of the plot as one number presented. More details are available in Shome (2023).

Statistical analyses

Each dependent variable (i.e., individual nutrients) was predicted with a repeated measure design across time and between treatments for select growth stages during the summer and for the winter months. Samples were collected and analyzed during winter to estimate movements in pools of nutrients. Additionally, differences between both pinhead square and first flower and first flower and cutout were analyzed to show variations in nutrient patterns relative to reproductive growth stages.

Samples were analyzed using JMP PRO 16 statistical software (SAS Institute Cary, NC, USA) at alpha level of 0.1. ANOVA and GLM for randomized complete block design with addition to Tukey's HSD (alpha level 0.1) test to compare means for a significant difference. Data were checked for normality using QQ plots and Levene's test for homogeneity of variance to determine the assumptions were met. Multiple linear regression was used to compare pools for complete nutrient cycling. Samples were analyzed by site-year because the location changed between years.

Results

We present results by nutrient pool to streamline the comparison of VFS treatments and site-years. Soil data are presented first to establish the baseline for available nutrients and explain why we focused on K to illustrate site-year variation resulting from the change in location between years. Variations in plant concentrations are described because nutrient uptake was influenced by differences in soil availability. Lastly, nutrient dynamics in pore water from below the rooting zone is presented to discuss the potential for nutrient losses due to leaching from the system.

Soil Nutrient Pool

Soil fertility varied by site-year, despite the plots being spatially adjacent and in the same soil map unit. Comparison of bare ground treatments at the pinhead square growth stage illustrated differences in the baseline soil fertility between site-years (Table 5.1). The most notable differences between the sites were for the 0-10 cm depth where Ca, K, and Mn concentrations were considerably greater in 2021 than 2022. At the pinhead square stage, the first sampling during the reproductive growth stage, Ca, K, Mg, Mn, and P in the 0-10 cm depth were greater in 2021 compared to 2022 for each treatment (Figure 5.1). Soil K was above the optimal level during all measured reproductive growth stages in 2021 and below optimal levels in 2022. There were only small shifts in soil K during reproductive growth with lasting transitions from below to above or above to below optimum soil K in either year. While not significant, all treatments with LM in the field had numerically greater nutrient concentrations during reproductive growth stages in the 0-10 cm depth compared to bare ground (VFS of 90 cm) in both years (Figure 5.1). For example, in 2022 the bare ground treatment was below the optimal soil test level for K, Ca, and Mg at first flower. Concentrations of Ca and K in 2021 increased one week after first flower for all treatments, but in 2022 increases in K occurred one week earlier in the LM treatments (Figure 5.1).

Nutrient concentrations in the 10-30 cm depth were lower than the 0-10 cm depth in both years (Table 5.1 and Figures 5.1 & 5.2). There were no treatment differences for nutrient concentration at the 10-30 cm depth (Figure 5.2).

Clover Biomass and Nutrient Pool

Clover biomass had a significant interaction between time (reproductive growth stages sampled) and VFS width treatments in 2021 (p-value <0.0001), but not in 2022 (Figure 5.3). In 2021, the medium VFS (30 cm) width significantly decreased (p-value <0.0001) across time while the narrow VFS (0 cm) VFS width did not. In 2022, there were no differences between the treatments, however when the medium VFS (30 cm) treatment was analyzed independently, biomass significantly decreased over time from pinhead square to cutout (p-value = 0.08).

The K concentration in clover biomass was not significantly different between clover treatments across all time points, but comparison at select growth stages showed some treatment differences in 2021. These direct comparisons showed that the narrow VFS treatment (0 cm) in 2021 had numerically greater K at pinhead square, first flower, and cutout. The clover K concentrations were more variable and numerically greater throughout the season in 2021 compared to 2022 (Figure 5.4).

Cotton Nutrient Pool

Cotton leaf nutrient concentration at pinhead square was not significantly different by treatment within years, however, there were some numerical differences between site-years (Table 5.2). Changes in nutrient concentrations from pinhead square to first flower and first flower to cutout varied by site-year and nutrient. In 2021, only changes in Ca and Mn relative to first flower were significantly different by treatment. In contrast, all six of the observed nutrients in 2022 were significantly different by treatment as determined by at least one change relative to first flower. Ca, K, and P in the cotton leaves from pinhead square to first flower in the bare ground (90 cm VFS) treatment had low variability when compared to treatments with clover in 2022. These nutrients also had a greater concentration overall at the first flower and pinhead square growth stages than other treatments with clover. The bare ground cotton nutrient status of K, P, and Mg also had less change from first flower to cutout, but P and Mg had a greater nutrient concentration at cutout than first flower (Table 5.2). Interpretations of nutrient contributions for optimal yield were difficult as nutritional status varied over the reproductive growth stages, and we used sufficiency ratings for optimal yield to interpret nutrient levels which can have large ranges of nutrient concentrations.

Pore Water Nutrient Pool

In addition to nutrient pools in soil and plants, we quantified nutrients in the pore water that leached below the primary root zone. Variability in soil moisture conditions throughout the study resulted in inconsistent availability of samples (data not shown). Approximately 54 % of sampling times did not produce sufficient pore water below the root zone, which suggests that the potential nutrient loss due to leaching below the root zone was minimal. Even when samples were extractable, the amount of water available varied by sampling time. In 2021, pore water was less available in treatments that had a full stand of both cotton and clover. The bare ground in 2021 with only cotton growing also had limited availability. In 2022 after the first flower, no pore water could be collected. The amount of nutrients in the pore water was highly variable between sampling periods and numerically different between sampling times within treatment. Clover treatments did not affect the nutrient concentrations in pore water.

While not significantly different, some trends in nutrient content in the pore water were observed. The greatest nutrient concentrations in the pore water occurred at the pinhead square stage and decreased by cutout. The K in the water samples at pinhead square for 2021 ranged from 2-11 ppm and in 2022 3-26 ppm for individual samples. The variation of K within treatments was between 2-4 ppm in 2021 at pinhead square and 1-11 ppm in 2022 at pinhead square, showing the great variation and making it hard to interpret the data. The amount of K in the water after pinhead square decreased to cutout but had low nutrient concentrations from the week before the first flower to the week after the first flower compared to earlier sampling, with high variability between the samples in a treatment similar to pinhead square time samples data for K.

Nutrient Cycling During Winter Months

During the winter, the clover provided an additional nutrient sink that could take up nutrients and prevent losses from the rooting zone creating a future available nutrient pool. Potassium concentration in the soil from 0-10 cm was not significantly different by treatment, however, K was numerically greatest in 15 cm VFS width compared to bare ground in February and March (data not shown). The bare ground had 127 and 129 mg kg^{-1} of K for February and March 2022 respectively with the 15 cm being 35 and 23 mg kg^{-1} of K more than bare ground, respectively.

Cotton Yield

In 2021, the bare ground treatment had a yield of 5,166 kg ha^{-1}, which was not significantly different from the medium VFS treatment (79% of bare ground). The 0 cm VFS width was statistically lower than the bare ground in 2021 with only 3% of the bare ground yield. In contrast, there were no separations between treatments in 2022. In 2022, the bare ground had a yield of 630 kg ha^{-1}, with 97% of the bare ground yield for medium VFS width treatment (30 cm) and 75% of the bare ground yield for narrow VFS width treatment (15 cm).

Discussion

Cotton Response to Living Mulch

Significant fluctuations in cotton leaf nutrient status make interpretations of sufficiency for cotton production challenging. While 2021 had limited significant differences between VFS width treatments, the nutrient status difference between time points can be connected back to soil nutrient status. In 2021, K, Mg, and P in the 0-10 cm depth were above the level that a deficiency would occur (Table 5.1 and Figure 5.1), which may explain why there was no visible effect on yield between bare ground and the medium VFS treatments (Kissel & Sonon, 2008; Shome, 2023). In contrast, K and Mg were below sufficient levels in 2022 and P was close to the minimum sufficiency, suggesting that a yield response would occur 50% of the time when fertilizer is added (Kissel & Sonon, 2008). Calcium in both years was in the sufficiency range that yield response may only occur 50% of the time, but 2021 was near double the level of 2022. All of the sufficiency interpretations were within the same range regardless of treatment which may partially explain why there were no yield differences in 2022.

Nutrient sufficiency is determined through correlation with yield and timing of sampling. This trial was placed within a larger trial exploring seeding rates and other VFS widths for yield components (Shome 2023). This trial was focused on three replicates and three treatments each year with one seeding rate that was the same for both years. The yield in 2021 for 0 VFS width was only 3% of the bare ground yield due to limited cotton plant survival and producing bolls to contribute to yield. The fact that these trials had different yields in 2021 and 2022 makes interpretations difficult because environmental drivers and soil fertility were not controlled in this study. In particular, yield in 2022 was lower than in 2021, which likely reflects the early frost in that year, resulting in poor boll maturity, deer damage in 2022 for one replicate, and lower soil fertility, as shown previously (Shome, 2023). Variability in environmental drivers may have contributed to the large yield variations in both years and explain the lack of any relationships between nutrient concentrations in cotton leaves and cotton yield.

Potential of Living Mulch as a Nutrient Reservoir

Clover K concentration at first flower significantly differed between year but not between treatments of VFS with clover growing. In 2021, clover K concentration was greater in 2021 which also had sufficient soil K concentration (Figure 5.4). In 2022, clover K was lower, and soil test K was also insufficient. The overall total content of K in clover was affected by the amount of biomass from the year variation. The 2021 variation between treatments for biomass was likely related to the size of the cotton plants which were larger and shaded the clover, whereas 2022 had less of a shading effect because the cotton was shorter than in 2021. The biomass is the largest factor for total content even though the plants will luxury consume extra K from the soil by becoming nutrient reservoirs. The decomposition of nutrient-rich clover biomass likely contributed nutrients to the soil surface to be available for cotton. Phosphorus showed a similar relationship between clover nutrient concentration and biomass. There was an increase in the concentration of K and P in the clover over time in 2021, but a decrease in clover biomass for the medium VFS width (30 cm) occurred on soil with optimal nutrient status. In 2022, the biomass was consistent with less die-off during the sampling period and less overall nutrient concentration over time compared to 2021, reflecting in potential reductions in the clover nutrient reservoir when the soil fertility was lower.

We were able to leverage the changes in plot locations between the two years to show, despite different soil nutrient levels, both areas provided adequate fertility to the cotton that demonstrated system responses in different pools. For example, when the soil K was below the sufficient range in the bare ground treatment in 2022, the clover treatments did not luxury consume. In contrast, luxury consumption occurred in 2021 as indicated by the higher level of plant K. In a similar study conducted in Japan, Deguchi et al. (2010) found a white clover LM took up K and served as a potential trap crop for K. They reported that LM can reduce yield of corn and suggested K uptake by clover may have reduced availability for the corn, which may have resulted from their cutting of LM at the time of fertilization and the vigorous regrowth at the time from LM taking up most of the K. Their observations support that LM can take up available and excess K in the system which prevents loss from the system similar to the 2021 data for this study.

The LM biomass was impacted by shading as the cotton canopy closed from different above-ground growth responses. The re-establishment of clover has been shown to be effective in other studies using Durana® white clover to recover the soil surface (Sanders et al., 2017; Weisberger et al., 2024). The shading of clover also allowed for N to be traced in the system and provided to plants, supporting that nutrients can be returned to the system and become available to the cash crop during the season (Sanders et al., 2017).

All treatments in 2022 had low soil fertility, which would suggest there was an effect on cotton growth compared to sufficiency standards that would have a yield response 50% of the time, according to the Georgia soil test handbook (Kissel & Sonon, 2008). In spite of the lower soil fertility, the presence of LM allowed the cotton to respond and maintain numerically higher leaf K compared to treatments with no LM (Figure 5). Our results suggest that the presence of the clover cover crop and an adequate cotton stand did not reduce cotton yield (Shome, 2023). The winter soil test K was higher for treatments with more clover, suggesting the potential for maintaining soil nutrients for the next season.

The use of water samples to interpret K or P leaching from the system does not always provide data that show cover crop effects (Isse et al., 1999). In our study, the amounts of pore water were not consistent during either year, but the small volumes that were collected indicate a low potential for nutrient leaching below the root zone. During the summer period when we started sample collection relative to the time when the cotton was shading out clover in 2021 pore water samples decreased in volume until none could be collected later during the growing season. While the shading out of LM in corn trials balanced the moisture equilibrium, our data suggest that cotton has a different soil moisture equilibrium (Sanders et al., 2018).

Challenges, Limitations, and Opportunities

The use of perennial cover crop like the LM that is alive year-round creates an increased water demand due to two plants taking water during the cash crop growing season. For example, Sanders et al. (2018) found that volumetric water content decreased over the course of the growing season in corn grown with a LM system. We did not directly measure soil moisture in this study, but we did see a reduction in the quantity of pore water from all treatments that could be extracted as the reproductive growth stages of cotton progressed. While the need for increased soil moisture during the year is not large, cotton yields can be maintained in a LM system being watered using standard bare-ground cotton production recommendations from the University of Georgia (Hand et al., 2023; Shome, 2023). Another study with a LM of Kura clover in a corn production system in Wisconsin and Minnesota showed that yield was not significantly different from conventional management even under drought conditions (Alexander et al., 2023). Of course, supplying an adequate amount of water for plant survival is essential in any system, but if yield is not significantly affected by the lower soil moisture with a perennial cover crop the potential for nutrient losses to leaching is reduced. Furthermore, the no-till management necessary in a LM system can help to maintain greater soil moisture compared to conventional tillage in the Piedmont (Endale et al., 2002). In addition to potentially reducing nutrient losses due to leaching, the LM system provides the benefit of increased infield biodiversity throughout the year compared to traditional monoculture crops with only one plant in the field at a time.

One limitation of this study was the challenge of tracking nutrient fluxes and quantifying the size of nutrient pools in soils, plants, and pore water. Each pool of nutrients was highly variable which likely reflects a wide range of environmental differences over the growing season along with varying responses of cotton and clover to available nutrients during that time. The samples were taken when water was potentially not moving from rain events, and sample times based on growth stages led to an incomplete picture of nutrients leaving the system. The pore water samples can suggest potential losses but a complete cycling of nutrients is difficult to do in a field study. Another limitation for measuring the complete cycling of nutrients was not being able to take cotton biomass samples at each sampling time, which prevented the determination of total nutrients in that pool. Instead, we were only able to track nutrient fluxes in cotton based on leaf concentrations and not total nutrient content of plants. Future studies should account for changes in total nutrient pools for the entire system to better understand fluxes and potential reservoirs of nutrients for subsequent years of production.

Conclusion

The use of perennial cover crops as a nutrient reservoir has the potential for luxury consumption of nutrients like K. Luxury consumption provides the benefit of preventing nutrients from leaving the system. When soil K level was below the optimal level from the start of reproductive growth, it resulted in greater fluctuations of nutrient status in the cotton during the reproductive growth when living mulch was present. In the winter, the greater amount of clover coverage area retained higher soil K. When proper stand was established for adequate yield (i.e., 30 cm VFS width in 2021), clover biomass significantly decreased as cotton reproductive growth progressed. When the clover biomass decreased, K concentration in clover, cotton, and soil was maintained or improved. There was a similar pattern in bare ground with the added benefit of K being maintained in the clover reservoir and reducing the vulnerability of loss from the system. The ability of the perennial clover cover crop to hold excess nutrients like K and not reduce availability to the cotton when excess is not available illustrates how the clover can work as a nutrient reservoir to improve nutrient use efficiency and potentially reduce negative impacts on the environment.

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Table 5.1. Mehlich 1 soil nutrients and soil pH at pinhead square from 90 cm VFS (bare ground) (n = 3) for both 2021 and 2022 at 0-10 cm depth and 10-30 cm depth (standard error in parentheses).

Year	Depth	pH	Ca	K	Mg	Mn	P	Zn
	cm		------------------------- mg kg^{-1} -------------------------					
2021	0-10	6.1 (0.2)	958 (95)	147 (3)	81 (12)	62 (7)	35 (10)	4.1 (0.4)
2021	10-30	5.9 (0.2)	540 (36)	51 (9)	50 (7)	40 (2)	8 (3)	1.1 (0.2)
2022	0-10	5.7 (0.1)	557 (72)	102 (19)	72 (7)	36 (6)	23 (2)	4.5 (0.3)
2022	10-30	6.0 (0.3)	413 (61)	53 (14)	49 (9)	25 (7)	4 (1)	0.8 (0.1)

Table 5.2. Cotton leaf nutrient concentration at pinhead square (PN) and differences (%) between sample times for three VFS width clover treatments over two years. Sample times included pinhead square (PN), first flower (FF), and cutout (CO).

		Year				
		2021		2022		
		----Width of Vegetation Free Strip (cm)----				
Nutrients	Growth Stage	30	90	15	30	90
		%				
Ca	PN	1.74	1.60	1.47	1.43	1.37
	PN-FF	0.16*	-0.65*	-0.55*	-0.59*	0.01*
	FF-CO	-0.25*	0.34*	0.41*	0.44*	-0.46*
K	PN	1.82	1.65	1.98	2.15	1.79
	PN-FF	0.70	0.60	0.86*	0.85*	0.55*
	FF-CO	-0.21	-0.11	-0.31*	-0.14*	0.10*
P	PN	0.56	0.58	0.83	0.87	0.73
	PN-FF	0.004	0.17	0.49*	0.48*	0.28*
	FF-CO	0.07	-0.03	-0.26*	-0.23*	-0.04*
Mg	PN	0.27	0.29	0.33	0.33	0.29
	PN-FF	-0.05	-0.13	-0.15	-0.08	-0.03
	FF-CO	-0.06	-0.05	0.14*	0.09*	-0.06*
Mn	PN	76.54	59.55	90.96	102.95	71.40
	PN-FF	1.27*	-22.60*	-11.35*	-27.83*	15.85*
	FF-CO	-0.34	2.34	8.90*	26.89*	-36.51*
Zn	PN	47.97	42.70	40.45	40.22	38.49
	PN-FF	16.20	12.78	10.48	8.10	7.25
	FF-CO	0.49	-1.86	-6.24*	-1.64*	3.11*

* Indicates significant differences (α=0.10) between VFS widths for nutrient concentration differences between pinhead square and first flower (PN-FF), and between first flower and cutout (FF-CO) within each year. (VFS of 90 cm is bare ground)

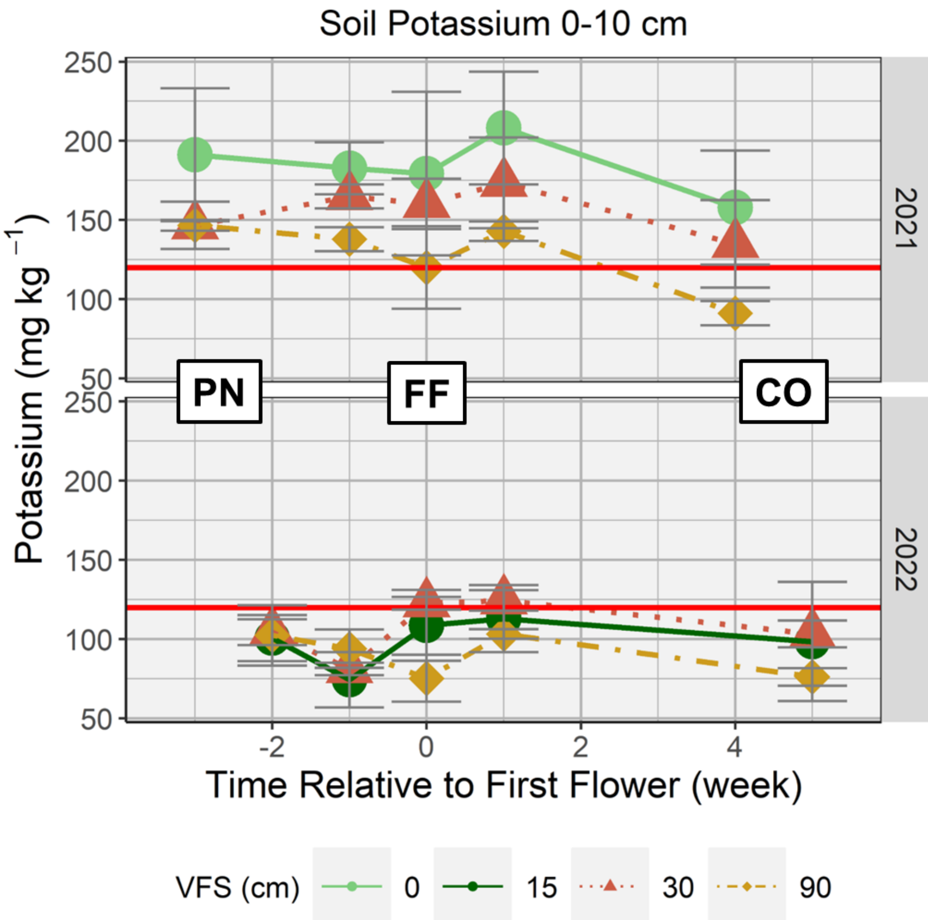

Figure 5.1. Soil potassium from 0-10 cm at different growth stages for single-year trials in 2021 and 2022. Growth stage -2 or -3: is pinhead square (PN), -1: week before the first flower, 0: first flower (FF), 1: week after the first flower, 4 or 5: weeks after first flower for cutout (CO). Three treatments of bare ground (90), medium VFS width of clover (30), and narrow VFS width of clover (0 in 2021 or 15 in 2022). The red line indicates the lower boundary of the range for medium soil K test (121-250), which is defined as a level sufficient to prevent a deficiency with an expected yield response about 50% of the time. Error bars are standard errors.

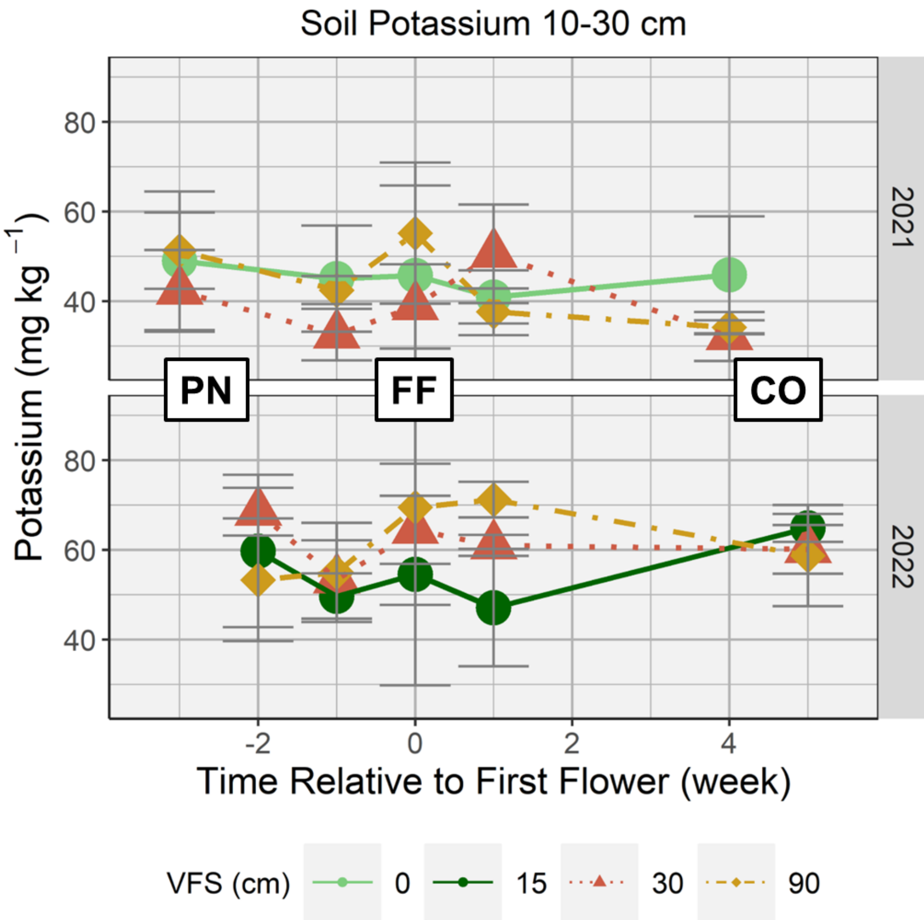

Figure 5.2. Soil potassium from 10–30 cm changes by growth stage for single-year trials in 2021 and 2022. Growth stage -2 or -3: is pinhead square (PN), -1: week before the first flower, 0: first flower, 1: week after the first flower (FF), 4 or 5: weeks after first flower for cutout (CO). The treatments represent bare ground (90), medium VFS width of clover (30), and narrow VFS width of clover (0 in 2021 or 15 in 2022). Error bars are standard errors.

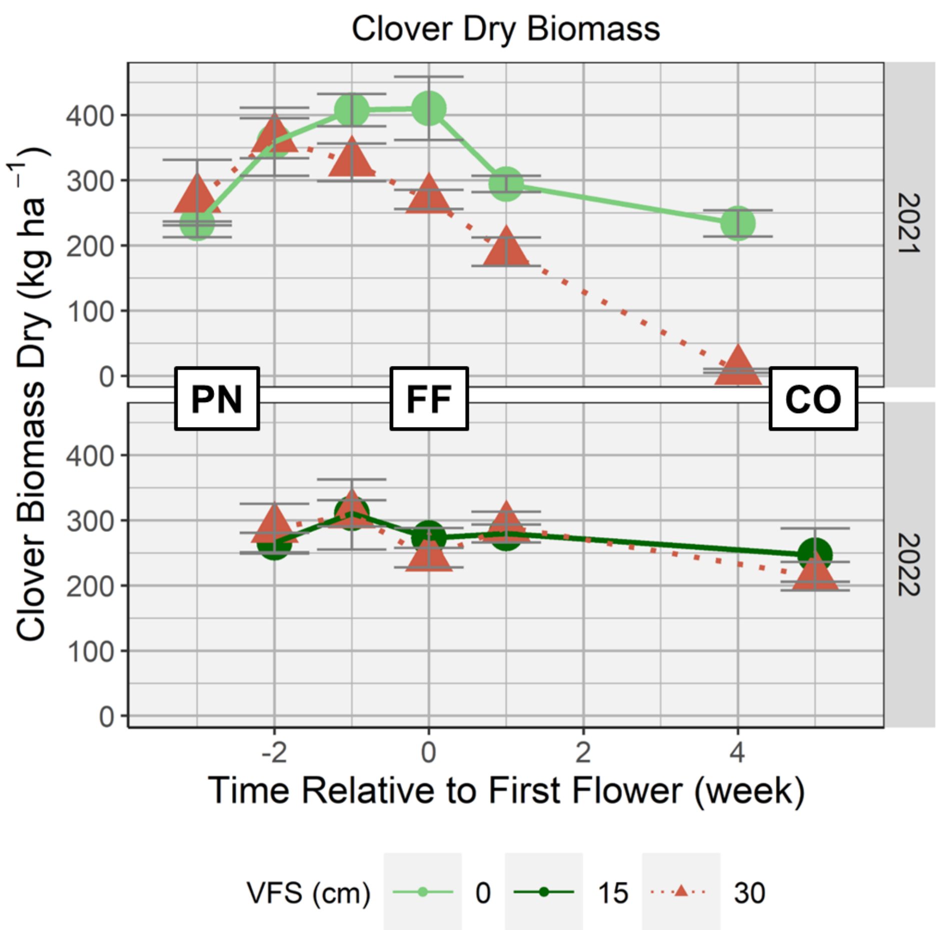

Figure 5.3. Clover above-ground dry biomass at different growth stages in 2021 and 2022. Growth stage -2 or -3: is pinhead square (PN), -1: week before the first flower, 0: first flower (FF), 1: week after the first flower, 4 or 5: weeks after first flower for cutout (CO). The treatments represent a medium VFS width of clover (30), and a narrow VFS width clover (0 in 2021 or 15 in 2022).

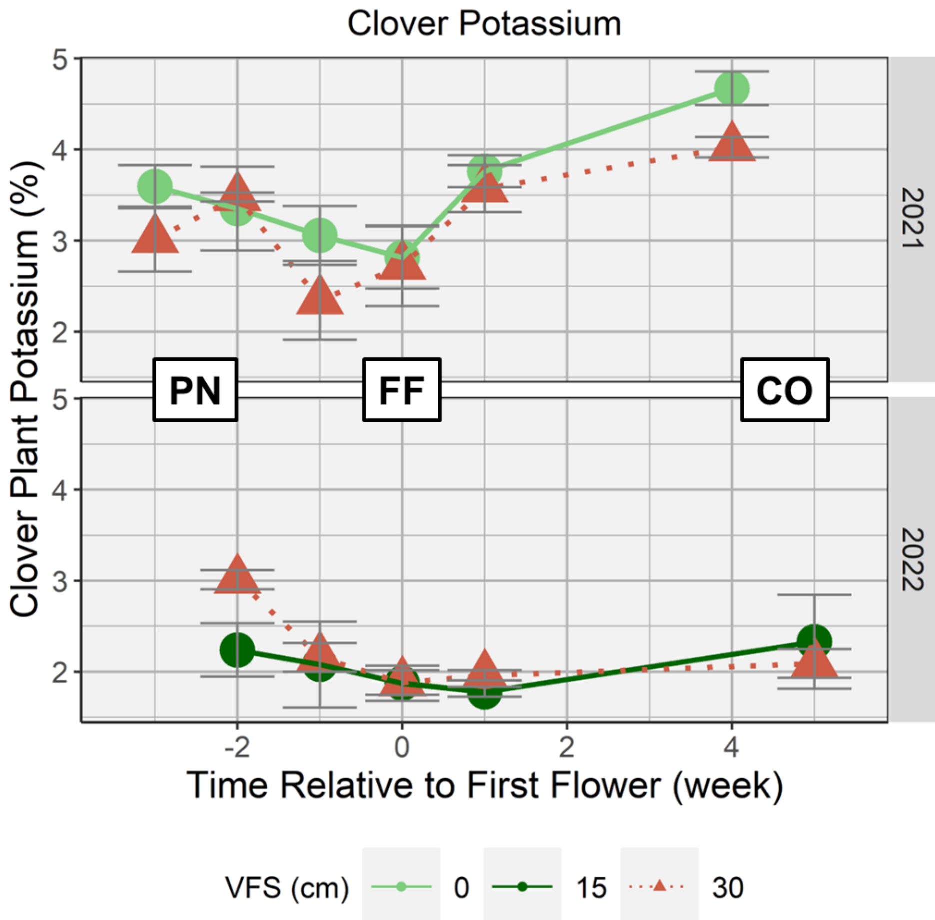

Figure 5.4. Clover above-ground plant potassium changes across growth stages for single-year trials in 2021 and 2022. Growth stage -2 or -3: is pinhead square (PN), -1: week before the first flower, 0: first flower (FF), 1: week after the first flower, 4 or 5: weeks after first flower for cutout (CO). The treatments represent a medium VFS width of clover (30), and a narrow VFS width of clover (0 in 2021 or 15 in 2022).

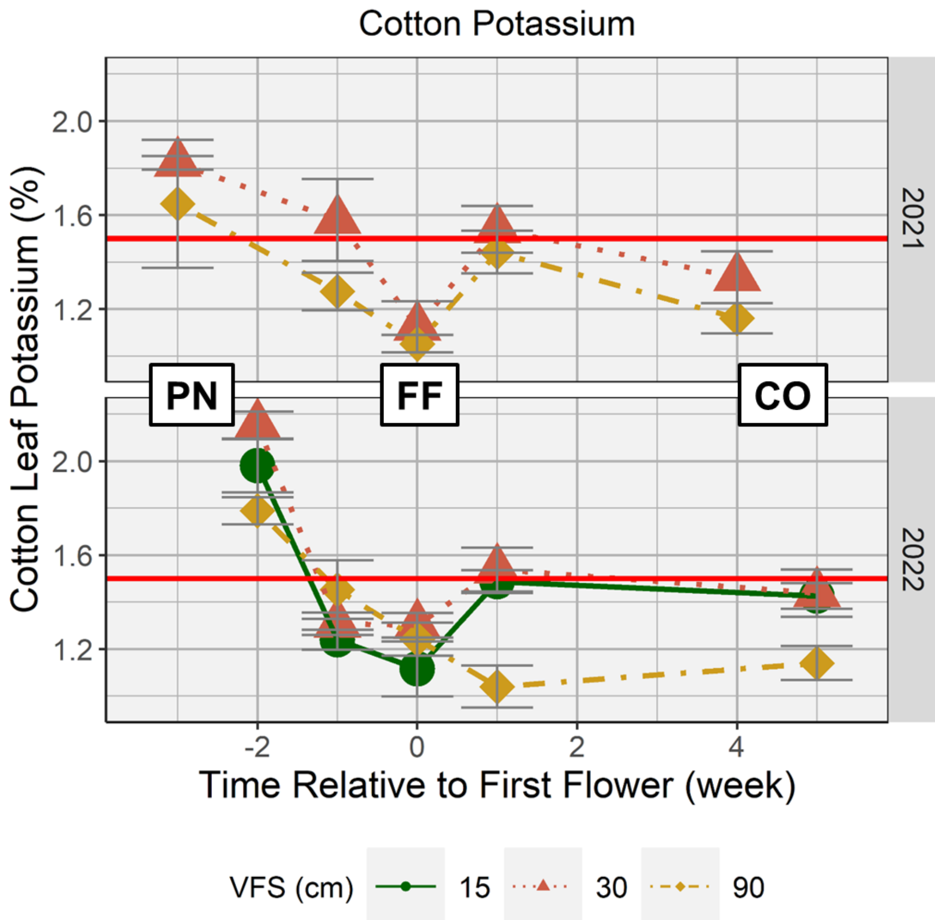

Figure 5.5. Cotton leaf potassium changes across growth stages for single-year trials in 2021 and 2022. Growth stage -2 or -3: is pinhead square (PN), -1: week before the first flower, 3: first flower (FF), 4: week after the first flower, 4 or 5: weeks after first flower for cutout (CO). Three treatments of bare ground (90), medium vegetation-free area of clover (30), and narrow vegetation-free area of clover (15). Red dashed line for optimal leaf K.

CHAPTER 6

CONCLUSIONS

This work quantifies the potential impacts of a living mulch (LM) on soil health and nutrient cycling for some soils commonly found in Georgia. Overall implications suggest that three to four years may not be sufficient to reliably detect changes in dynamic soil properties commonly used to assess soil health. Some benefits of the LM included contributions of potentially mineralizable N, improvement in water infiltration, and the potential for the LM to serve as a reservoir for K. The data collected for the first two data chapters allowed for the forming of pedotransfer functions (PTFs) that could be compared to generalized models for performance.

Beginning with information from the first two data chapters, comparisons of time, depth, and treatment had trends but limited significance. The interaction in these main effects was not significant in the trials but significant main effects occurred in some properties like bulk density. The bulk density in the cotton trial was increased at the time of sampling in the cereal rye treatment compared to bare ground and LM without time separation at a depth of 0-5 cm. This is likely a reflection of roller crimper impact on the surface that the other treatments that were lower bulk density did not get the impact. The sampling time did occur after cover crop termination and not time for the cover crops that were terminated to reverse the effects. The porosity in the cotton trial had the same effects as the bulk density but was measured with another adjacent core. The soil hydraulic properties also had limited effects but volumetric water content at the wilting point (WP) was lower for LM (α=0.1) than crimson clover and cereal rye. Lowering the WP can increase the range of available water content (AWC). Saturated hydraulic conductivity had a faster rate in LM (α=0.1) compared to other treatments when not separating years. Within years the LM rate increased (α=0.1) in 2021 and remained numerically greater after that, but effects were reduced with more time. The improvement in water getting into the soil and reduction in WP can potentially lead to greater hydraulic function from the use of LM. This is a positive improvement as growing two plants at the same time of cash crop and LM increases soil moisture needs. In irrigated fields when sampling the cotton at the cotyledon stage soil moisture was lower in samples from LM treatments at a depth of 9-25 cm compared to other treatments. Lower soil moisture is a potential concern that needs to be managed, but other benefits like increased infiltration can aid in this.

At the pecan orchard site in the Coastal Plain, there were some numerical rate increase of water infiltration in wheel track rows. The statistical difference was that the compaction between heavy wheel track areas to lower traffic areas was 15 cm hr^{-1} faster in lower traffic areas (α=0.1). Over time, there was a numerical reduction in the infiltration rate between wheel tracks, though differences between infiltration rates in both placements were not statistically different after four years of continuous clover growth. This provides evidence that no differences occurring that LM is mitigating some of the negative effects from compaction. This is similar to the results in porosity and bulk density in these trials.

Soil chemical properties from all the trials showed a similar pattern that of K. In general, the K built up over time in LM treatments. In the nutrient cycling study, the LM worked as a nutrient reservoir for K. In a cotton trial the LM luxury consumed the K when readily available in the soil. Then, when the cotton cash crop was at the critical growth stage for the K is needed by the cotton, the LM was senescing, releasing K held back into the system. Also, during the winter, LM had greater K (α=0.1) in a month when sampled compared to bare ground. Total organic carbon (TOC) did not always have a statistical increase over time in LM treatments at the soil surface 0-5 cm from the three trials. The TOC increased by year at a rate of 0.12% when averaging all three trials from the LM treatment. The building of soil carbon is a desired quality and an indicator of soil health.

Soil hydraulic properties are commonly sought after by producers, but measurements are difficult because of time commitments and high cost. Consequently, PTFs are often used to estimate the hydraulic properties from easier to measure physical and chemical soil properties. While there are large database models available to do this, they are not geographically specific and can have variability when focusing on a specific area. The more geographically specific GA models performed better than general models like Rosetta3 and Saxton and Rawls (2006) models. Similar to those models, texture and TOC were important coefficients to predict hydraulic properties. Both factors were sampled with a push probe which is easier to operate and can represent an area with composite samples. Typically, when hydraulic properties are analyzed, they are specific to one point and require several measurements to create a composite. The ability to predict properties that are expensive and time-consuming to collect with more accessible information can benefit growers and consultants. Additionally, also it can be difficult to find commercial soil testing labs that analyze soils for these hydraulic properties in Georgia and the USA which adds to the need for improved prediction models. Overall, a LM system can provide soil physical, chemical, and hydraulic benefits as outlined, but sufficient time is needed (potentially more than three years) for statistical improvements.

APPENDICES

A Appendix Information for Chapter 2

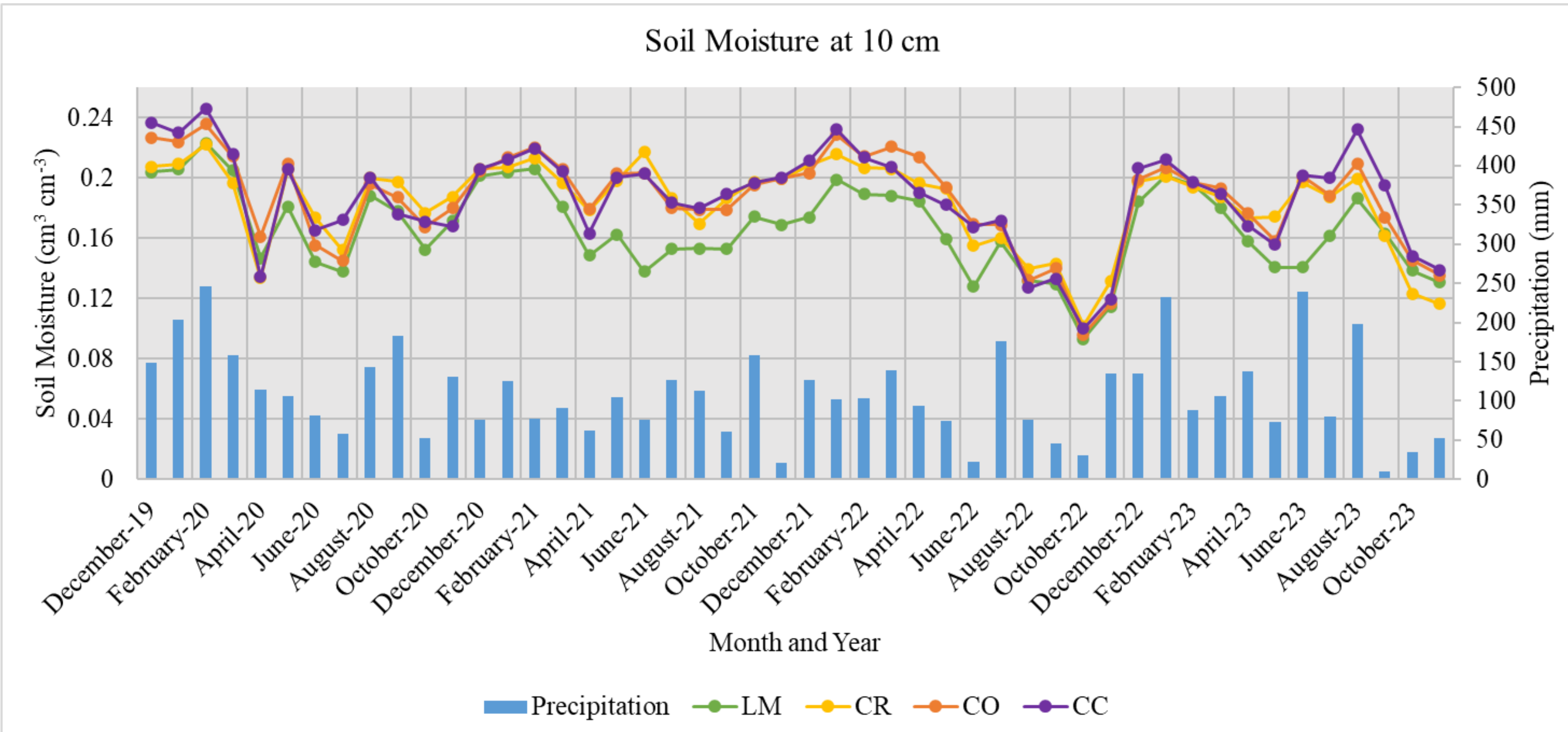

Figure A.1. Soil Moisture at 10 cm depth four cover crop treatments over four years monthly averages. The bars are the total monthly precipitation. Treatments were living mulch (LM), cereal rye (CR), crimson clover (CC), and bare ground (CO).

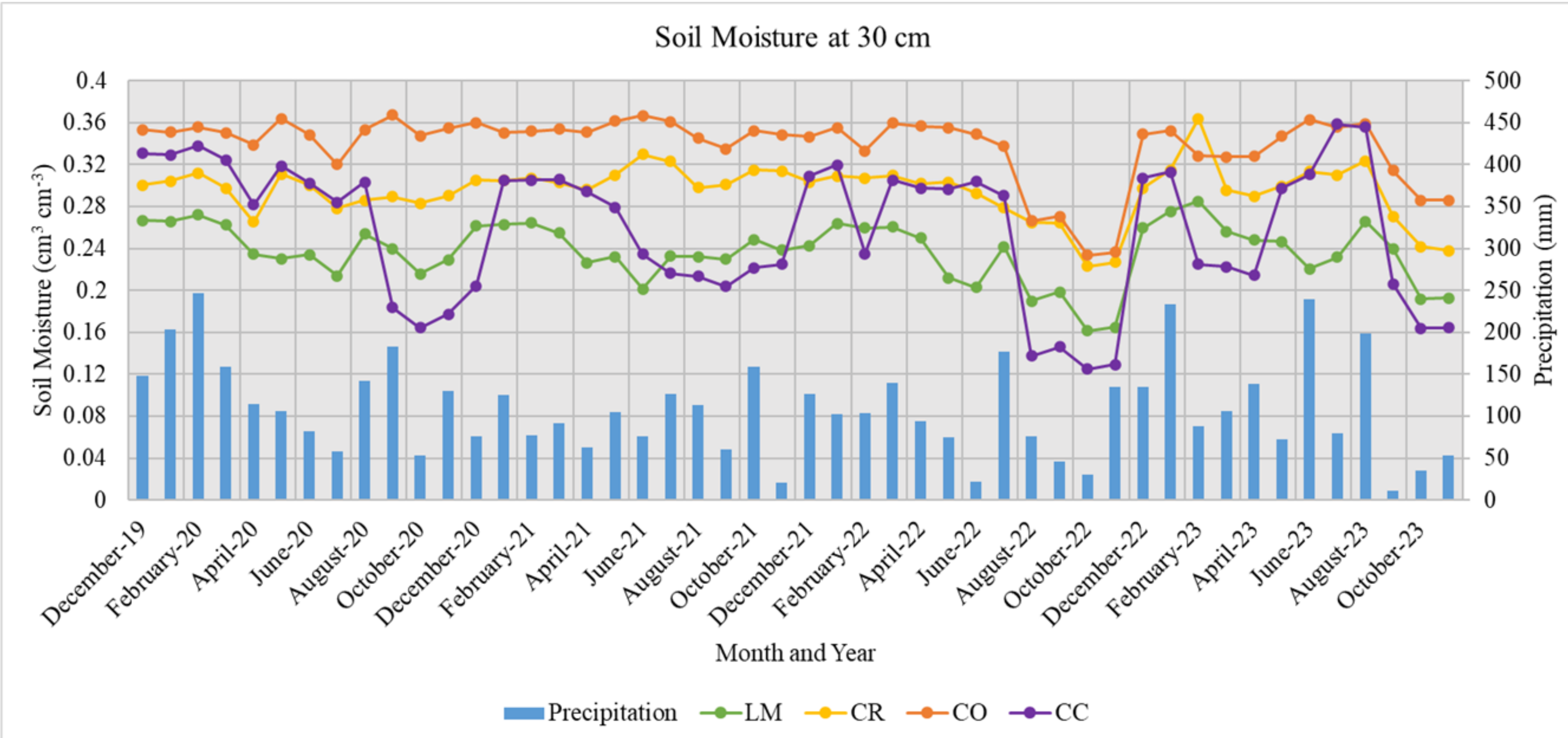

Figure A.2. Soil Moisture at 30 cm depth four cover crop treatments over four years monthly averages. The bars are the total monthly precipitation. Treatments were living mulch (LM), cereal rye (CR), crimson clover (CC), and bare ground (CO).

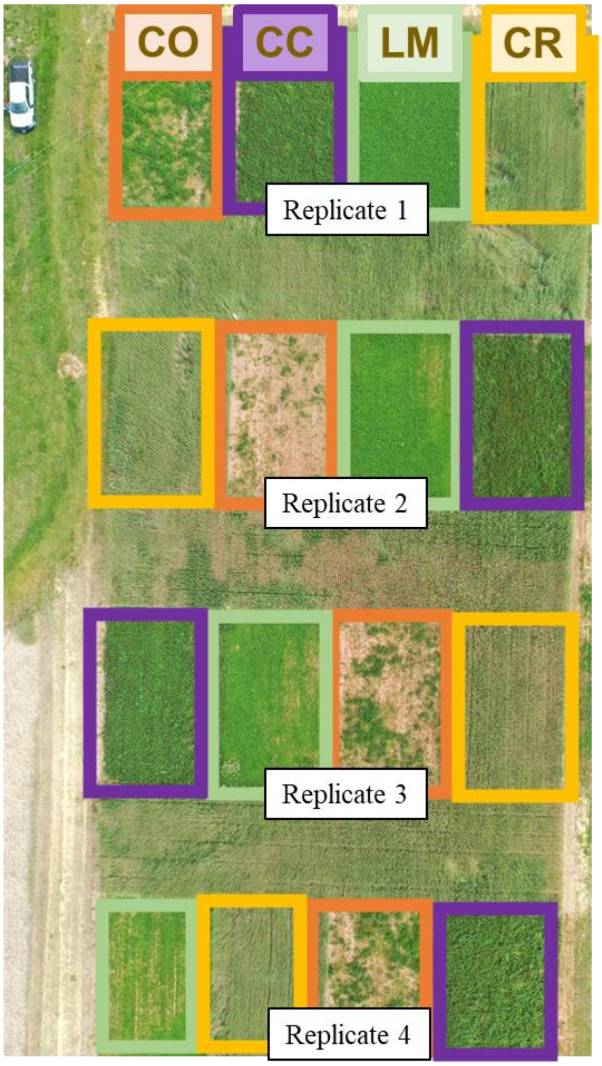

Figure A.3. Plot map for chapter 2 that had four cover crop treatments of living mulch (LM), cereal rye (CR), crimson clover (CC), and bare ground (CO) with four replicates. The same layout in the clay percent by depth charts following.

Table A.1. Clay percent at a depth of 0-5 cm by plot and replicate means with plot layout the same as figure A.3.

Replicate	Clay at 0-5 cm				Replicate Means
	--------------------------%--------------------------				
1	27	25	19	24	24
2	18	29	17	16	20
3	22	29	20	26	24
4	12	18	22	22	19

Table A.2. Clay percent at a depth of 5-15 cm by plot and replicate means with plot layout the same as Figure A.3.

Replicate	Clay at 5-15 cm				Replicate Means
	--------------------------%--------------------------				
1	27	29	26	30	28
2	25	41	21	14	25
3	33	38	34	31	34
4	18	24	23	29	24

Table A.3. Clay percent at a depth of 15-30 cm by plot and replicate means with plot layout the same as Figure A.3.

Replicate	Clay at 15-30 cm				Replicate Means
	--------------------------	%	--------------------------		
1	49	44	37	38	42
2	58	50	44	25	45
3	62	65	59	67	63
4	30	43	54	55	46

Table A.4. Soil characterization data for P1 pedon in a pecan orchard near Stapleton, GA (Fine, kaolinitic, thermic Typic Kandiaquult).

Horizon	Depth	Sand	Silt	Clay	pH H_2O†	pH $CaCl_2$	TOC	Ca	Mg	K	Na	Al
	cm	-----------	%---------	-----			%	-------	-------meq	100 g soil^{-1}	-------	-------
Ap	0-29	66.7	25.7	7.6	4.77	4.17	1.76	1.48	0.42	0.07	0.08	0.01
Btg1	29-67	35.6	22.3	42.1	3.81	3.21	0.28	0.16	0.27	0.04	0.11	0.23
Btg2	67-102	25.2	17.3	57.5	3.99	3.39	0.19	0.06	0.40	0.02	0.11	0.24
Btg3	102-154	29.3	16.4	54.3	3.70	3.1	0.17	0.16	0.51	0.04	0.11	0.26

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, Na, are NH_4OAc exchangeable bases, TOC= total organic carbon.

Table A.5. Soil characterization data for P3 pedon in a pecan orchard near Stapleton, GA (Fine, kaolinitic, thermic Plinthic Kandiudult).

					pH							
Horizon	Depth	Sand	Silt	Clay	H_2O†	$CaCl_2$	TOC	Ca	Mg	K	Na	Al
	cm	-------------%--------------					%	---------------meq 100 g soil^{-1}--------------				
Ap	0-13	80.4	14.57	5.03	6.36	5.76	0.97	2.95	0.29	0.23	0.08	0.01
E	13-28	78.9	14.11	6.99	5.75	5.15	0.36	0.75	0.15	0.08	0.02	0.03
E2	28-38	70.3	18.8	10.9	4.81	4.21	0.20	0.39	0.14	0.08	0.11	0.14
Bt1	38-81	37.9	14.1	48	5.30	4.70	0.19	1.87	0.82	0.10	0.20	0.03
Bt2	81-104	32.3	10	57.7	4.48	3.88	0.09	1.17	1.53	0.08	0.10	0.05
Btv1	104-138	28.7	10.4	60.9	4.74	4.14	0.08	0.30	0.71	0.06	0.04	0.05
Btv2	138-160	28.1	11.4	60.5	4.33	3.73	0.08	0.21	0.60	0.04	0.04	0.04

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, Na, are NH_4OAc exchangeable bases, TOC= total organic carbon.

Table A.6. Soil characterization data for LM3 pedon in a row crop site near Midville, GA (Fine, kaolinitic, thermic Plinthic Kandiudult).

					pH							
Horizon	Depth	Sand	Silt	Clay	H_2O†	$CaCl_2$	TOC	Ca	Mg	K	Na	Al
	cm	-------------%--------------					%	---------------meq 100 g $soil^{-1}$--------------				
Ap	0-22	73.4	16.46	10.14	6.24	5.64	0.57	2.15	0.45	0.37	0.08	0.09
Bt1	22-70	26.8	9.75	63.45	6.46	5.86	0.13	3.27	1.02	0.22	0.09	0.00
Bt2	70-99	18.5	8.7	72.8	6.02	5.42	0.11	2.74	0.71	0.07	0.04	0.01
Btv1	99-130	15.5	10.4	74.1	4.73	4.13	0.09	1.91	0.79	0.05	0.04	0.00
Btv2	130-150+	13.25	10.25	76.5	4.49	3.89	0.05	1.46	0.99	0.05	0.03	0.00

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, Na, are NH_4OAc exchangeable bases, TOC= total organic carbon.

Table A.7. Soil characterization data for LM2 pedon in a row crop site near Midville, GA (Fine, kaolinitic, thermic Plinthic Kandiudult).

Horizon	Depth	Sand	Silt	Clay	pH H_2O†	pH $CaCl_2$	TOC	Ca	Mg	K	Na	Al
	cm	-------------%--------------					%	---------------meq 100 g $soil^{-1}$--------------				
Ap	0-32	82.35	11.72	5.930	5.65	5.05	0.39	1.24	0.22	0.15	0.01	0.00
Bt1	32-56	19.50	7.75	72.75	5.89	5.29	0.16	3.69	1.41	0.31	0.08	0.00
Bt2	56-93	18.35	7.25	74.40	4.80	4.20	0.15	3.86	1.61	0.21	0.06	0.29
Btv1	93-122	27.55	6.65	65.80	4.51	3.91	0.09	3.04	1.97	0.11	0.05	0.08
Btv2	122-150+	30.65	6.20	63.15	4.35	3.75	0.08	2.26	1.99	0.09	0.05	0.17

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, Na, are NH_4OAc exchangeable bases, TOC= total organic carbon.

Table A.8. Soil characterization data for JPC pedon in a cotton field near Watkinsville, GA (Fine, kaolinitic, thermic Typic Kanhapludults).

Horizon	Depth	Sand	Silt	Clay	pH H_2O†	pH $CaCl_2$	TOC	Ca	Mg	K	Na	Al
	cm	-------------%--------------					%	---------------meq 100 g soil^{-1}--------------				
Ap	0-14	21.65	32.20	46.15	5.98	5.38	0.88	3.27	0.49	0.28	0.07	0.00
Bt1	14-44	14.55	25.35	60.10	6.26	5.66	0.45	3.47	0.66	0.07	0.11	0.00
Bt2	44-68	19.85	27.95	52.20	6.34	5.74	0.26	1.33	0.45	0.02	0.02	0.00
Bt3	68-118	35.20	37.40	27.40	5.05	4.45	0.05	0.63	0.27	0.02	0.04	0.01
Bt4	118-154	38.75	38.70	22.55	4.74	4.14	0.03	0.25	0.09	0.01	0.05	0.01
BC	154-172	32.60	43.25	24.15	4.72	4.12	0.03	0.18	0.06	0.02	0.04	0.01
C	172-200+	35.75	43.55	20.70	4.71	4.11	0.02	0.21	0.06	0.02	0.02	0.02

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, Na, are NH_4OAc exchangeable bases, TOC= total organic carbon.

C Field Descriptions of Profiles

<u>Sample ID:</u> Coastal Plain Pecan Orchard P1
<u>Taxonomic Classification:</u> Fine, kaolinitic, thermic Typic Kandiaquult
<u>General Description:</u> This soil was sampled in a pecan orchard on nearly level ground (2020 by Chandler Gruener and Matthew Levi)

Profile:	Depth:	(Colors are for moist soil.)
Ap	0 to 29 cm	Very dark grayish brown (10YR 3/2) sandy loam; abrupt boundary.
Btg1	29 to 67 cm	Gray (10YR 6/1) clay; clear bound; few red (2.5YR 4/6); few yellowish brown (10YR 5/4).
Btg2	67 to 102 cm	Yellowish brown (10YR 5/8) clay; mixed 50/50 gray (10YR 6/1); gradual boundary.
Btg3	102 to 154+ cm	Gray 60% (2.5Y 6/1) clay; 40% yellowish brown (10YR 5/6).

<u>Sample ID:</u> Coastal Plain Pecan Orchard P3
<u>Taxonomic Classification:</u> Fine, kaolinitic, thermic Typic Kandiudult
<u>General Description:</u> This soil was sampled in a pecan orchard on nearly level ground (2020 by Chandler Gruener and Matthew Levi)

Profile:	Depth:	(Colors are for moist soil.)
Ap	0 to 13 cm	Dark grayish brown (2.5Y 4/2) loamy sand; abrupt bound.
E	13 to 28 cm	Light yellowish brown (2.5Y 6/3) loamy sand; clear bound.
E2	28 to 38 cm	Light yellowish brown (2.5Y 6/4) sandy loam; clear bound.
Bt1	38 to 81 cm	Yellowish red (5YR 5/8) clay; gradual boundary.
Bt2	81 to 104 cm	Strong brown (7.5YR 5/8) clay; few yellow mottles; brownish yellow common (10YR 6/6) mottles.
Btv1	104 to 138 cm	Yellowish brown (10YR 5/6) clay; common mottles red (2.5YR 4/6).
Btv2	138 to 160+ cm	Brownish yellow 45% (10YR 6/6) clay; 45% red (2.5YR 4/6) mottles; few olive yellow (2.5Y 6/6).

<u>Sample ID:</u> Coastal Plain Row Crop LM3
<u>Taxonomic Classification:</u> Fine, kaolinitic, thermic Plinthic Kandiudults
<u>General Description:</u> This soil was sampled in a corn field on nearly level ground going towards a slope (2021 by Chandler Gruener and Matthew Levi)

Profile:	Depth:	(Colors are for moist soil.)
Ap	0 to 22 cm	Dark grayish brown (10YR 4/2) Sandy Loam.
Bt1	22 to 70 cm	Strong brown (7.5YR 5/8) Clay.
Bt2	70 to 99 cm	Strong brown (7.5YR 5/8) Clay.
Btv1	99 to 130 cm	Color (5YR 5/8) Clay; concentrations dark yellowish brown (10YR 4/6); depletions light grey (5YR 7/1).

Btv2	130 to 150+ cm	Strong brown (7.5YR 5/8) Clay; concentrations dark yellowish brown (10YR 3/4); depletions light grey (5YR 7/1).

Sample ID: Coastal Plain Row Crop LM2
Taxonomic Classification: Fine, kaolinitic, thermic Plinthic Kandiudults
General Description: This soil was sampled in a corn field on nearly level ground going towards a slope (2021 by Chandler Gruener and Matthew Levi)

Profile:	**Depth:**	**(Colors are for moist soil.)**
Ap	0 to 32 cm	Brown (7.5YR 4/2) Loamy Sand.
Bt1	32 to 56 cm	Yellowish red (5YR 5/8) Clay; concentrations dark yellowish brown (10YR 3/4); depletions brownish yellow (10YR 6/8).
Bt2	56 to 93 cm	Red (2.5YR 4/8) Clay; concentrations dark yellowish brown (10YR 3/4); depletions light grey (7.5YR 7/1).
Btv1	93 to 122 cm	Red (2.5YR 4/8) Clay; concentrations dark yellowish brown (10YR 4/6); depletions grey (7.5YR 6/1).
Btv2	122 to 150+ cm	Red (2.5YR 4/8) Clay; concentrations dark yellowish brown (10YR 3/4); depletions light grey (5YR 7/1).

Sample ID: Piedmont JPC Cotton
Taxonomic Classification: Fine, kaolinitic, thermic Typic Kanhapludult
General Description: This soil was sampled in a cotton field on nearly level ground very few to progressing to common mica concentrations (2022 by Chandler Gruener and Matthew Levi)

Profile:	**Depth:**	**(Colors are for moist soil.)**
Ap	0 to 14 cm	Yellowish red (5YR 4/6) sandy clay loam; moderate coarse granular structure; friable; abrupt bound.
Bt1	14 to 44 cm	Red (2.5YR 4/6) clay; moderate coarse subangular blocky structure; fine; 3% Mn concentrations reddish black (2.5YR 2.5/1); clear boundary.
Bt2	44 to 68 cm	Red (2.5YR 4/6) clay loam; moderate subangular blocky; fine; 1% Mn concentrations reddish black (2.5YR 2.5/1); clear boundary.
Bt3	68 to 118 cm	Dark red (2.5YR 3/6) sandy clay loam; moderate medium subangular blocky; friable; clear boundary.
Bt4	118 to 154 cm	Dark red (2.5YR 3/6) sandy loam; weak medium subangular blocky; friable; clear boundary.
BC	154 to 172 cm	Red (2.5YR 4/6) sandy loam; weak medium subangular blocky; very friable; concentrations reddish brown (7.5YR 6/8) 3% few; depletions dark reddish brown (5YR 3/4) 3% few; clear boundary.
C	172 to 200+ cm	Weak red (10R 4/4) sandy loam; massive; very friable; concentrations reddish black (2.5YR 2.5/1) 3% few; depletions reddish yellow (7.5YR 6/6) 5% few.