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Cover Crop Treatment Impacts on Selected Soil Health Indicators in Two Tennessee Long-term No-till Corn-Soybean Rotations

Adam A. Zimmerman
University of Tennessee, Knoxville, azimme16@vols.utk.edu

To the Graduate Council:

I am submitting herewith a thesis written by Adam A. Zimmerman entitled "Cover Crop Treatment Impacts on Selected Soil Health Indicators in Two Tennessee Long-term No-till Corn-Soybean Rotations." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental and Soil Sciences.

Forbes R. Walker, Major Professor

We have read this thesis and recommend its acceptance:

Neal S. Eash, Sindhu Jagadamma, Shawn Hawkins

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Cover Crop Treatment Impacts on Selected Soil Health Indicators in Two Tennessee Long-term No-till Corn-Soybean Rotations

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Master of Science

Degree

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DEDICATION

I dedicate this work to my wife, Natalie, whose love, support, dedication, and strength allowed me to chase a lifelong dream. I will never have the words nor time to repay you for this gift of opportunity. I could not have asked for a better partner to navigate this journey and to help limit the impact on our children. Our family thrives on your grace and light, thank you for everything.

To my children, Ellah & River, thank you for enduring the sacrifices and challenges that my schooling created. Please know that I always wished I could be with you while I worked, but I knew I had to do this for our family. Your futures are the driving force behind my success. I love you more than you will ever know, and I could not be prouder to be your dad.

I would also like to dedicate this thesis to Nathan & Nancy Hammons (Natalie's parents) and my parents (Allen & Kathy Zimmerman) for the priceless support throughout all of this. The kid-watching, meals, and support was more help than you can ever understand, thank you.

Additionally, I dedicate this work to my personal mentor, Dr. Neal Eash. I would not be the scientist or individual I am today without your example. You are the reason I ever considered graduate school and you facilitated my success throughout. This thesis would not have been possible without you. Your impact goes beyond academics and this campus. I look forward to your continued guidance in my life, both personally and professionally.

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ABSTRACT

Soil hydraulic conductivity (K_{sat}) and soil microbial biomass carbon (SMB-C) estimates in Tennessee no-till corn (*Zea mays* L.) and soybean (*Glycine max* L.) rotation systems may be changed with cover crops. This study assessed differences in K_{sat} rates and SMB-C values under common cover crop treatments of two no-till corn and soybean rotation systems in west and middle Tennessee. Wheat (*Triticum aestivum* L.), cereal rye (*Secale cereale* L.), wheat/crimson clover (*Trifolium incarnatum* L.), cereal rye/crimson clover, a five species mix (containing cereal rye, crimson clover, whole oats (*Avena sativa* L.), daikon radish (*Raphanus sativus* L.), and hairy vetch (*Vicia villosa* L.)), a three species mix (containing wheat, crimson clover, and Austrian winter peas (*Pisum sativum* L.)), and another three species mix (containing cereal rye, crimson clover, and Austrian winter peas) were planted as winter cover crops and compared with a control (no cover crop) at two University of Tennessee Research & Education Centers: the University of Tennessee's Research and Education Center at Milan (UTRECM) and the Middle Tennessee Research & Education Center at Spring Hill (MTREC). The UTRECM site was dominated by two soil series: Providence silt loam (Fine-silty, mixed, active, thermic Oxyaquic Fragiudalf) and Center silt loam (Fine-silty, mixed, active, thermic Aquic Hapludalf). The MTREC site also had two soil series: Maury silt loam (fine, mixed, active, mesic Typic Paleudalf) and Huntington silt loam (fine-silty, mixed, active, mesic Fluventic Hapludoll). K_{sat} rates were measured using a SATURO Dual-Head Infiltrometer from METER Group Inc. (Pullman, Washington). SMB-C values were estimated using the microBIOMETER® test from Prolific Earth Sciences (Montgomery, New York). The K_{sat} and SMB-C data from both locations provided no statistically significant treatment results and had large spatial variability. It is hypothesized that the lack of significant differences for infiltration or SMB-C between cover

crop treatments is due to the current agricultural management on both landscapes which provides a good habitat for earthworms and other soil macro-arthropods and thus the development of extensive preferential flow pathways resulting in soil moisture regimes that also provide suitable conditions for soil microbial biomass.

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CHAPTER 1

GENERAL INTRODUCTION

In the Southeastern USA, changes in weather patterns are causing agricultural production issues for farmers (such as flooding and droughts) that requires research to identify possible climate change adaptations (Adams et al., 1998). Floods and droughts are a couple of the climate change weather pattern impacts that concerns producers (Adams et al., 1998). Both of these issues can potentially devastate a year's entire crop as well as have tertiary impacts (such as eutrophication or erosion) on the surrounding ecosystem (Mustroph, 2018). Intense rainfall can turn some fields into ponds which causes planting delays, crop failure, yield losses, nutrient losses to leaching/runoff, and soil erosion (Mustroph, 2018). Similarly, droughts can cause crop failure, yield losses, degradation of soil organic matter (SOM), and soil erosion (Wilhite, 2000). Some research indicates that more resilient soils are less affected by both excess and limited rainfall (Lal, 2015). Soils regarded as "healthy" can have more resilience to negative weather-based challenges (Lal, 2015).

Soil Health

Soil health (SH) is defined as the continued capacity of soil to function as a vital living system to sustain biological productivity, maintain environment quality, and promote plant, animal, and human health and habitation (Macewan and Carter, 1996; Doran and Zeiss, 2000). Soil quality (SQ) is often used synonymously with soil health (Gregorich and Carter, 1997). Doran and Parkin (1997) describe a framework for separation between the terms based on a conceptualization of soil quality being more related to how a soil can function, whereas soil health relates to the soil being a living dynamic resource which feed directly into plant health (Lal, 2015). The terminology used in the literature used to describe these ideas or concepts has changed as technology and the collective knowledge allowed for more a nuanced understanding of these complex systems known as soils. Figure 1 shows the timeline for the evolution throughout modern recorded history of the terminology used for soil assessments and soil's ability to function (Powlson, 2020; Karlen et al.,1990).

The United States Department of Agriculture (USDA) and Natural Resource Conservation Service (NRCS) state that healthy soil is the foundation of productive, sustainable agriculture (2020). The USDA-NRCS lists indicators used to track soil health for a variety of soil physical, chemical, and biological properties as well as how the properties relate to soil health (2021). These properties include soil organic matter (SOM), soil erosion, infiltration, water holding capacity (WHC), pH, microbial biomass, and biological diversity (USDA-NRCS, 2021). Figure 2 shows the interactions among the physical, chemical, and biological soil properties which make up soil health. The above references should be used to intuit the dynamic interactivity and inherent complexity that soil environments and, even more so, larger scale environments typically function as.

Cover Crops

Cover crops are non-economic crops grown between the harvesting and planting of cash crops (Singer, 2008). Cover crops are typically planted in the fall in Tennessee and terminated prior to planting of the cash crops the following spring. Before "cover crops" became popular, there was an ancient practice known as "green manuring" which involved growers intentionally turning under (with early plows) certain plants (grasses, weeds, or planted crops) to improve the functioning of the soil (Fageria, 2007). This practice has been dated back to the Romans of 300 B.C., who turned under legumes like fava beans (*Vicia faba* L.) and lupines (*Lupinus* spp.) for

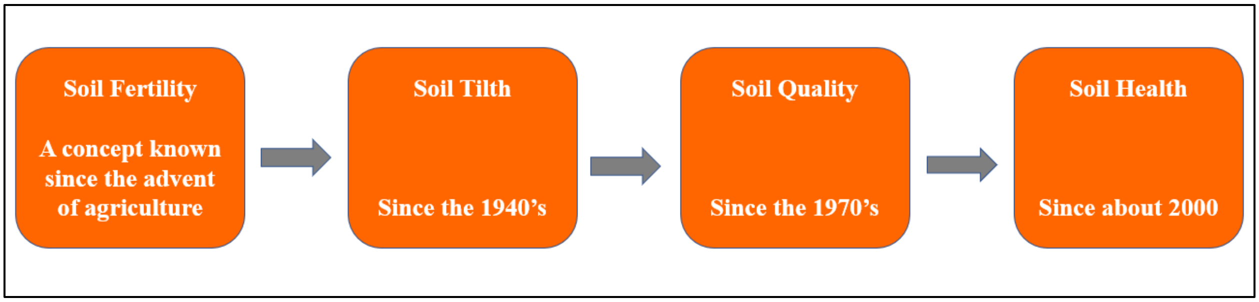

Figure 1. Development of terminology for assessing soils and their ability to function. (Adapted from Powlson, 2020.)

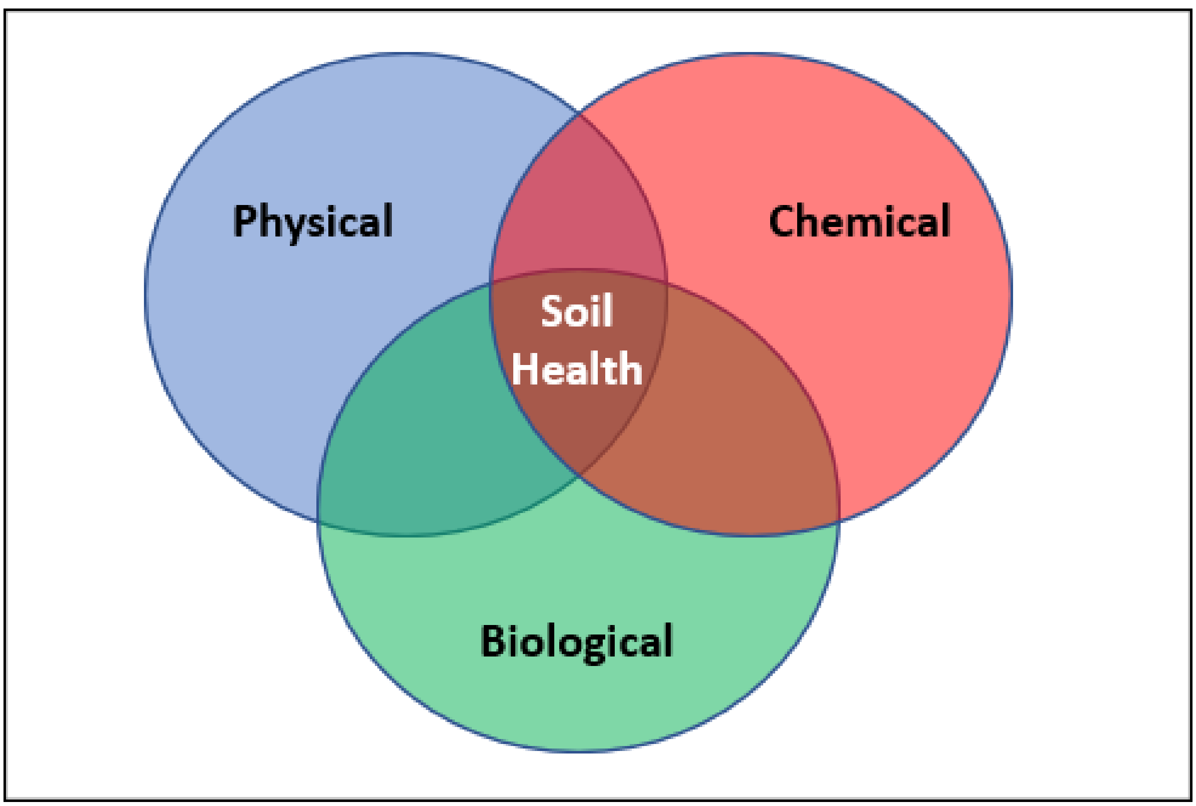

Figure 2. Soil health is comprised of the infinite dynamic interactions between the physical, chemical, and biological soil properties (Adapted from Toor et al., 2021)

soil improvement and persisted even in early America where buckwheat (*Fagopyrum esculentum* L.) was used in a similar fashion by European colonists (Fageria, 2007). There are many different species and varieties of cover crops grown in different parts of the world. In the Southeastern USA, common cover crops include winter wheat (*Triticum aestivum* L.), cereal rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.), whole oats (*Avena sativa* L.), daikon radish (*Raphanus sativus* L.), hairy vetch (*Vicia villosa* L.), and Austrian winter peas (*Pisum sativum* L.) (MacLaren et al., 2019). Cover crops have many benefits, including weed suppression (Fageria et al., 2005), reduction of soil erosion (Kaspar et al., 2001), trapping excess nutrients (Kaspar and Singer, 2008), fixing nitrogen (for legumes) (Blevins et al., 1990), adding organic matter to the soil (Hartwig and Ammon, 2002), and even reducing compaction and mitigation of plow pans (Chen and Weil, 2009).

Cover crops also provide many ecological/ecosystem services such as: increasing SOM; improving soil physical properties; weed, pest, and disease controls; improvements in food, fiber, fuel, and feed production; plant-nutrients (including nitrogen (N), phosphorus (P), potassium (K)) and carbon (C) cycling improvements/sustainability in soils; water cycling/quality improvements; overall soil quality improvement; and overall air quality improvement (Ramroudi and Sharafi, 2013; Blanco-Conqui et al., 2015). This can also benefit area wildlife by providing more edible biomass on the landscape as well as area pollinators with more flowers to pollinate (Blanco-Canqui et al., 2015; Bryant et al., 2013). Some producers harvest cover crops (sometimes called double-cropping). For example, winter wheat can be used as a cover crop then grown to maturity and harvested, which can add to the farm revenue for the year (Shapiro et al., 1992). Double-cropping is more prevalent when commodity prices are high compared to when they are low, otherwise producers just terminate the cover crop and plant their cash crop.

Ongoing work evaluates the forage benefits of some cover crops which could feed the livestock used to remove the cover crop (which also fertilizes the landscape with raw manure) in hopes of assisting farmers to find another value-added benefit of cover crop use (Drewnoski et al., 2018).

Cover crops have been shown to increase infiltration in different low-residue systems (under both conventional tillage (CT) and no-till (NT)) and protect the soil surface from disintegration by raindrop impacts (Nouri et al., 2019a; Folorunso et al., 1992; de Almeida et al., 2018). The dead roots of cover crops become pathways for water flow (Yu et al., 2016). Cover crops such as daikon radish can also reduce compaction (Chen and Weil, 2009). The increase in organic matter from the cover crop residue can improve soil aggregation and aggregate stability in the soil profile, which can increase the water holding capacity (Kern, 1995). Soil microbes typically respond with increased activity (Vukicevich et al., 2016) and generally speaking, the overall health and resilience of the soil is better when cover crops are included (Ghimire et al., 2019). These processes are also a function of no-till systems because the elimination of tillage allows these beneficial processes to take place (Nunes et al., 2018). In long-term no-till corn (*Zea mays* L.) and soybean (*Glycine max* L.) cropping systems, earthworms can transform soil profiles (Ashworth et al., 2017a), and the soil can move much more water through preferential flow paths (Van Schaik et al., 2013). Poiseuille's Law for laminar flow states a doubling of a channel's radius equates to a 16 times increase in flow potential (Gerke, 2006). For example, if a root channel with a radius of 1-mm is expanded by an earthworm to have a radius of 2-mm, this single channel can now transmit 16 times more water. At a field scale this should have greater effect on combatting more intensive rainfall events by increasing water infiltration rates, reducing runoff, and reducing soil erosion.

No-tillage

Prior to the Dust Bowl era (1931-1939), moldboard plow (MP) tillage was the most common land preparation practice of farmers in parts of Oklahoma, Kansas, and northern Texas (Huggins and Reganold, 2008). The 1960's brought the beginnings of research and methods of no-till (NT) agriculture. No-tillage is defined by the USDA/NRCS as a method of farming that limits soil disturbance with tillage to manage the amount, orientation, and distribution of crop and plant residue on the soil surface throughout the year (2021). No-till planting methods can be traced back to 8000 B.C. when "planting sticks" were used to plant seeds in individual holes prior to the earliest plows (Huggins and Reganold, 2008). Since the 1970's, the University of Tennessee has played an important role in no-till research. The University of Tennessee Institute of Agriculture's (UTIA) West Tennessee Research and Education Center (WTREC) in Jackson, TN still maintain some long-term no-till research plots dating back to 1981 (Nouri, 2017). The USDA and NRCS both list many benefits from reducing or discontinuing tillage, which includes reduced erosion, increased organic matter, and improved soil structure (2021). Epplin and Vitale (2013) indicated that adoption of no-till may require some potential equipment upgrade costs, but eventually the savings of time and costs (fuel/passes on fields) that no-till can bring are evident. NRCS describes the practice of no-till farming as an easy method for improving many soil properties and indicators of soil health/quality by simply ceasing to disturb the soil profile with tillage (2021). No-till has also been shown to increase total and dissolved organic C, aggregate stability (Ceylan, 2020), increase infiltration rates (Nouri et al., 2018), as well as earthworm populations (Storck, 1996; Ashworth et al., 2017) when compared with conventional tillage (CT) in a continuous cotton (*Gossypium hirsutum* L.) system (with and without cover crops), continuous corn (with cover crop) rotations, corn/wheat/soybean rotations, and soybean/wheat rotations systems.

Water Infiltration

The term infiltration has many different meanings within the scientific literature and researchers have measured infiltration in as many different ways. Sometimes infiltration is used as a replacement for drainage (reduction in ponded volume over time), while other times it used as the measure of difference in collected runoff from applied precipitation (Precipitation – Runoff = Infiltration). The term infiltration may even have a different context depending on the industry (agriculture, forestry, stormwater). This study uses infiltration as defined as the ability of a soil to transmit water under a gradient (Fryar and Mukherjee, 2019). This concept is based on Darcy's Law, which details how fluids move through a porous medium (Oosterbaan and Nijland, 1994). Saturated hydraulic conductivity is determined by the texture of a soil because texture is closely linked to soil pore space (Rawls et al., 1998). Saturated hydraulic conductivity (which is often denoted K_{sat}, K_{fs}, or K_s) is a value which corresponds to how much water a given soil can move when the profile is saturated or at field capacity for soil moisture (Skaggs, 1996). Reynolds et al. provides the methodological standards for measuring infiltration using various ring devices (2002).

Soil water infiltration is an important landscape function that soils play. In urban settings, the increase in impervious surfaces from development requires that we engineer systems to adequately deal with and process the runoff precipitation that does not enter the ground. In agriculture, it is important to capture rainfall through infiltration and store it in the soil for use by plants during the growing season, as well as reduce the potential for flooding. Cover crops provide protection to the soil from the impact of raindrops and are important in reducing soil erosion and slowing down the flow of runoff over the landscape surface. By slowing the flow of water on the soil surface there is more time for the precipitation to infiltrate into the soil profile, and thus reduce runoff. Cover crops have been shown to increase infiltration rates in continuous cotton, under both tillage and no-till, with significantly higher rates under no-till cotton compared to conventionally-tilled cotton systems (Nouri et al, 2018). The inherent variability of soils is one of the more challenging aspects when studying soil physical and hydrological processes.

Soil Microbial Biomass

Soil microbial biomass (SMB) is often tied to soil health (SH) and is regularly used as a parameter in SH evaluations as shown by Pankhurst et al. (1995) and Toor et al. (2021). Soil microbial populations undergo many changes throughout a calendar year such as fluxes in overall microbial population numbers and the composition of microbial communities present (Lauber et al., 2013). Temperature, moisture, nutrients, and oxygen are some factors that can affect soil microbial population dynamics (Castro et al., 2010). This information may be useful as a method of tracking SMB changes over time, before or after amendment additions, or throughout management transition periods. Measurement of soil microbial biomass carbon (SMB-C) can be accomplished with a variety of processes such as fumigation-incubation (FI), fumigation-extraction (FE), direct microorganism counts, and substrate-induced respiration (SIR) with FI and FE being the most popular methods, though they are certainly not the only possible methods. (Rice et al., 1997). The FI method involves fumigating a soil sample with chloroform and then incubating it for 10 days wherein the remaining microbes feed on other lysed microbial cells and convert the organic C to CO_2, which is then used for analysis (Rice et al., 1997). FE begins exactly the same way as FI but following fumigation the organic C, which was released by the lysed microbial cells, is extracted with a salt solution (0.5 *M* K_2SO_4) and then analyzed (Rice et al., 1997) Most SMB-C analysis is expensive and requires longer time periods than farmers would prefer. SMB-C analysis also typically requires specialized equipment or chemicals, but there are some developing methods which could be much easier, faster, and cheaper than the standard laboratory analyses.

Research Objectives

Previous studies have demonstrated that no-till in combination with cover crops can increase infiltration in continuous cotton systems in west Tennessee (Nouri et al., 2018). We were also interested in evaluating any possible differences the cover crop treatments could be having on the soil microbial biomass in corn-soybean rotations. As previously mentioned, SMB-C is a commonly used indicator in soil health assessments. The overall objectives of this study were to assess saturated hydraulic conductivity (K_{sat}) rates and soil microbial biomass carbon values (SMB-C) for differences among corn and soybean rotations in long-term no-till systems in Tennessee under common cover crop treatments at different timescales.

Saturated Hydraulic Conductivity (K_{sat})

- Objective 1: Determine if K_{sat} rates vary significantly among selected cover crop treatments (including control) in similar corn-soybean rotation cropping systems.

- Objective 2: Determine if K_{sat} rates of cover crop treatment plots vary significantly among recently established (3 years) and older (8 years) corn-soybean rotation cropping systems.

Soil Microbial Biomass (SMB)

- Objective 1: Determine if SMB-C values vary significantly among selected cover crop treatments (including control) in similar corn-soybean rotation cropping systems.

- Objective 2: Determine if SMB-C values of cover crop treatment plots vary significantly among recently established (3 years) and older (8 years) corn-soybean rotation cropping systems.

CHAPTER 2

MATERIALS AND METHODS

INTRODUCTION

Cover crop research plots at two locations within the University of Tennessee's Institute of Agriculture (UTIA) system of research centers were sampled during this study, one location is in middle Tennessee and the other site is in west Tennessee. The plots were evaluated for statistically significant differences of two soil health (SH) indicators. Measurements were obtained for infiltration and SMB-C under various cover cropping treatments in a no-till, corn (*Zea mays* L.)-soybean (*Glycine max* L.) rotation system. Water infiltration, measured as saturated hydraulic conductivity (K_{sat}), was used as an indirect measure of differences in soil structure while SMB was measured in units of µg SMB C/g soil under the selected cover cropping treatments of this no-till, corn-soybean rotation system. The K_{sat} measurements were recorded using a commercially-available automated dual-head infiltrometer, while SMB-C measurements were obtained using a commercially-available product which visually estimates soil microbial biomass carbon (µg microbial biomass C/gram of soil) and soil microbial fungal:bacterial (F:B) ratio. Because these cover crop plots were planted to fulfill other research functions and at a five-year temporal difference, the available cover crop treatments at each location did have variations. For example, there is not a direct match for the wheat + crimson clover (WCC) treatment at the University of Tennessee Research and Education Center at Milan (UTRECM), nor for the cereal rye + crimson clover (CRCC) treatment at the Middle Tennessee Research and Education Center (MTREC) in Spring Hill. Similarly, the soil health mix (SHM) treatment at Milan, soil health mix - A and soil health mix - B (SHM-A and SHM-B) treatments at Spring Hill were all tested as multi-species mixtures, with no focus on the exact species contained within the respective mixes at each location.

The University of Tennessee's Research and Education Center at Milan (UTRECM)

The west Tennessee site is located at UTRECM in Gibson county. This experiment was established in 2013 as a planting method study to evaluate differences between surface broadcasted seed or drilled seed on a no-till landscape. The experimental design is a randomized complete block design (RCBD) with 4 blocks and 14 treatments or plots per block as shown in Figure 3. All areas are managed for no-till production row cropping following the Tennessee NRCS guidelines for seeding rates and crop management. This site falls under the coverage of a center-pivot irrigation system and occasionally receives additional moisture if the adjacent experimental research areas require additional precipitation.

Following termination of the cover crops each spring, the plots are planted in a corn-soy rotation. Corn was grown in 2019 and soybeans were be grown in 2020. This location has two primary soil series: Providence silt loam (Fine-silty, mixed, active, thermic Oxyaquic Fragiudalf) and Center silt loam (Fine-silty, mixed, active, thermic Aquic Hapludalf). Prior to 2013, this area was used for production row cropping and a three-year nitrogen (N) study.

Each plot measures approximately 13' x 32' (3.96m x 9.75m) and was planted with cover crops during the non-cropping season. The cash crops are rotated each cropping season, but the plots receive the same cover crop treatments annually. Table 1 summarizes the seeding rates for the cover crops being evaluated in this study: cereal rye (*Secale cereale* L. or CR), wheat (*Triticum aestivum* L. or W), a mix of cereal rye + crimson clover (*Trifolium incarnatum* L. or CRCC), a five species NRCS "soil health" mix containing: cereal rye, crimson clover, whole oats (*Avena sativa* L.), daikon radish (*Raphanus sativus* L.), and hairy vetch (*Vicia*

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Block 4	408 3	409 4	410 7	411 8	412 1	413 2	414 13
	401 12	402 11	403 10	404 9	405 6	406 5	407 14
Block 3	308 7	309 8	310 6	311 5	312 12	313 11	314 10
	301 2	302 1	303 4	304 3	305 13	306 14	307 9
Block 2	208 9	209 10	210 2	211 1	212 5	213 6	214 3
	201 7	202 8	203 14	204 13	205 12	206 11	207 4
Block 1	108 3	109 4	110 2	111 1	112 7	113 8	114 11
	101 14	102 13	103 5	104 6	105 10	106 9	107 12

F R E D A L L E N P L O T S

Treatments

1	CR + CC (B)
2	CR + CC (D)
3	CR + HV (B)
4	CR + HV (D)
5	Wheat (B)
6	Wheat (D)
7	Cereal Rye (CR) (B)
8	Cereal Rye (CR) (D)
9	SHM x 2 (B)
10	SHM x 2 (D)
11	SHM (B)
12	SHM (D)
13	Control (B)
14	Control (D)

Figure 3. Experimental layout of cover crop experiment at Milan

Table 1. Cover crop treatment seeding rates for the UTRECM location (Milan).

Treatment	Cover Crop	Drilled rate (kg/ha)	Broadcast rate (kg/ha)
CRCC	Cereal Rye	26	33
	Crimson Clover	16	20
W	Wheat	84	110
CR	Cereal Rye	84	110
SHM	Cereal Rye	17	22
	Whole Oats	22	29
	Daikon Radish	2	2
	Crimson Clover	4	5
	Hairy Vetch	7	9
NC (control)	None	No planted cover	

villosa L. or SHM), and a no cover crop control (NC). The NC treatment means that no cover was intentionally planted on the site but does not mean that vegetation (in the form of volunteer winter annual weeds) did not grow between harvesting and planting. The plots were not treated with herbicide following harvest of the cash crops, only prior to planting of the cash crops (to terminate any weeds and cover crops present). This practice follows typical producer management for no-till agricultural systems which do not implement cover crops. This site has been under no-till management for at least 30 continuous years.

The University of Tennessee's Middle Tennessee Research and Education Center at Spring Hill (MTREC)

The middle Tennessee site is located at MTREC in Maury county. This experiment was established in 2018 as a no-till cover crop trial evaluating common cover crop species and/or combinations (mixes) of these same species. The experimental design is a randomized complete block design (RCBD) of 4 blocks with 14 treatments or plots per block (Figure 4). All areas are managed for no-till production row cropping using the Tennessee NRCS guidelines for seeding rates and crop management. This site receives only natural rainfall for moisture.

Following termination of the of the cover crops each spring, the plots are planted in a corn-soy rotation. Soybeans were grown in 2019 and corn was grown in 2020. This location has two primary soil series: Maury silt loam (fine, mixed, active, mesic Typic Paleudalf) and Huntington silt loam (fine-silty, mixed, active, mesic Fluventic

Vineyard experiment

Block 1	101 7	102 5	103 10	104 11	105 6	106 14	107 4
	108 9	109 13	110 3	111 12	112 2	113 1	114 8
Block 2	201 11	202 2	203 3	204 7	205 12	206 4	207 6
	208 1	209 5	210 10	211 14	212 13	213 8	214 9
Block 3	301 13	302 6	303 8	304 14	305 12	306 4	307 11
	308 3	309 7	310 10	311 9	312 2	313 1	314 5
Block 4	401 1	402 4	403 9	404 5	405 11	406 2	407 3
	408 13	409 8	410 14	411 10	412 7	413 12	414 6

Hwy 31

Treatments

1	Control
2	Cereal Rye (CR)
3	Wheat (W)
4	Winter Oats (O)
5	Crimson Clover (CC)
6	Vetch (V)
7	W + V
8	W + CC
9	CR + V
10	CR + CC
11	SHM 1
12	SHM 2
13	SHM-A
14	SHM-B

Figure 4. Experimental layout of cover crop experiment at Spring Hill

Hapludoll). Prior to the current experiment, this area was used for crop variety trials as well as a long-term tall fescue dominated sod experiment.

Each plot measures approximately 10’ x 30’ (3.05m x 9.14m) and receives one cover crop treatment during the non-cropping season. The cover crops being evaluated in this study are: cereal rye (CR), wheat (W), a mix of wheat + crimson clover (WCC), a three species NRCS “soil health” mix containing wheat, crimson clover, and Austrian winter peas ((*Pisum sativum* L.) or SHM-A), a three species NRCS “soil health” mix containing cereal rye, crimson clover, and Austrian winter peas (SHM-B), and a no cover crop control (NC) (Table 2). The NC treatment means that no cover was intentionally planted on the site but does not mean that vegetation (in the form of volunteer winter annual weeds) did not grow between harvesting and planting. The plots were not treated with herbicide following harvest of the cash crops, only prior to planting of the cash crops (to terminate any weeds and cover crops present). This practice follows typical producer management for no-till agricultural systems which do not implement cover crops. This landscape has been under no-till management for at least 20 continuous years.

Sampling for Saturated Hydraulic Conductivity (K_{sat})

Infiltration data was observed at the two research locations during the period of November 2019 - May 2020 using a SATURO dual-head infiltrometer (DHI) (METER Group; Pullman, Washington). This instrument functions as an automated single-ring infiltrometer with two different pressure head levels. Table 3 illustrates the settings chart for the programming options included in the operator’s manual for the infiltrometer.

Table 2. Seeding rates for the sampled cover crop treatments at the MTREC site in Spring Hill.

Treatment	**Cover Crop**	**Drilled Rate (kg/ha)**
WCC	Wheat	28
	Crimson Clover	39
W	Wheat	84
CR	Cereal Rye	84
SHM-A	Wheat	28
	Winter Peas	10
	Crimson Clover	7
SHM-B	Cereal Rye	28
	Winter Peas	10
	Crimson Clover	7
NC (control)	None	No planted cover

The SATURO operator's manual (METER Group) provides the following equation:

$$K_{fs} = \frac{\Delta\,(i_1 - i_2)}{D_1 - D_2} \qquad \text{Equation 1}$$

where D_1 is the actual high-pressure head, D_2 is the actual low-pressure head, $\Delta = 0.993d + 0.578b$ (cm), i_1 is the infiltration rate at high-pressure head, and i_2 is the infiltration rate at low-pressure head. For Δ, d = depth of infiltrometer insertion (5.0 cm for SATURO) and b = radius of infiltrometer ring (7.6 cm), therefore Δ = 9.40 cm for this study. The instrument outputs an Excel spreadsheet with the raw 1-minute incremental data along with individual charts of the flux, pressure levels, and water usage values for each observation or completed test. This in-situ method of saturated hydraulic conductivity analysis requires no physical samples to be removed from the research plots.

Initially, ten measurements per cover crop plot for a total of 40 infiltration readings per treatment at each location were conducted; but afterwards, the measurements were reduced to six readings per cover crop plot for a revised total of 24 observations per treatment at each location (n = 40/24). This was done under consultation of University of Tennessee's Office of Information Technology (OIT) statistician Dr. Xioujuan (Julia) Zhu. The reduction in observations only resulted in a change in the third decimal place, which is beyond the precision of the method and deemed appropriate given the reduction in required sampling time.

Sampling for Soil Microbial Biomass Carbon (SMB-C)

Three soil samples per cover crop treatment plot (n = 12/treatment/location) were collected at the two research locations and the soil microbial biomass C data was analyzed (within 4 days of collection) in August 2020 using the microBIOMETER® rapid test (Prolific Earth Sciences, Montgomery NY). The microBIOMETER® system is a commercially available

Table 3. Setting chart for SATURO dual-head infiltrometer (adapted from SATURO operators manual, METER Group).

Soil Type	Soak Time (min)	Low Pressure Head (cm)	High Pressure Head (cm)	Hold Time at Pressure (min)	Pressure Cycles (count)	Total Run Time (min)
Dry loamy sand	25	5	10	15	3	115
Wet loamy sand	15	5	10	15	2	75
Dry silt loam	30	5	15	20	3	150
Wet silt loam	15	5	15	20	2	95
Dry clay (poor structure)	30	5	20	25	3	180
Wet clay (poor structure)	15	5	20	25	2	115
Dry clay (strong structure)	25	5	10	20	3	145

product which measures soil microbial biomass carbon (μg microbial biomass C/gram of soil) and soil microbial fungal:bacterial (F:B) ratio. The product kit is portable (smaller than a laptop), inexpensive (< $20 / sample), quick (< 30 minutes), and has a video tutorial. The analysis is completed using a free smartphone application. This method is minimally disruptive as it requires small soil probe (approximately 2.5 cm or 1 inch diameter) samples to be removed from the plots for analysis.

STATISTICAL ANALYSES

Saturated Hydraulic Conductivity (K_{sat})

Saturated hydraulic conductivity (K_{sat}) was measured between November 2019 and May 2020 at the two University of Tennessee Research and Education Centers where cover crop plots were previously established. K_{sat} data were analyzed using JMP Pro 15 (SAS Institute; Cary, North Carolina) after separating the replicated data by treatment and by location. The Shapiro-Wilk goodness of fit test rejected the assumption that the replicate K_{sat} data were normally distributed ($P< 0.05$); log transformed data were also not normally distributed (Shapiro-Wilk $P < 0.05$). Raw data from each location grouped by block did not display for homogeneity of the variance (Levene's test; $P < 0.05$).

A non-parametric approach was taken to analyze the K_{sat} data which lacked a normal distribution and constant variance between treatments. Medians were calculated for the block separated replicate K_{sat} measurements. Treatment median values were assessed using the Wilcoxon/Kruskal-Wallis test to determine if any statistically significant differences existed in the K_{sat} data by the cover crop treatment applied.

Soil Microbial Biomass

Replicate (3) soil samples (3.0 cm diameter x 7.5 cm deep) were collected in August 2020 from the cover crop treatment plots maintained at UTRECM and MTREC. Soil microbial biomass carbon (SMB-C, μg SMB C / g soil) measurements for the replicate soil samples were made using the microBIOMETER® (Prolific Earth Sciences; Montgomery, NY) rapid soil health test. The measured soil microbial biomass C data were statistically analyzed using JMP Pro 15 (SAS Institute; Cary, North Carolina).

CHAPTER 3

RESULTS AND DISCUSSION

RESULTS

Saturated Hydraulic Conductivity

There were no statistically significant differences in K_{sat} results between the cover crop treatments at locations UTRECM and MTREC (Wilcoxon/Kruskal-Wallis $P > 0.05$). Table 4 summarizes the calculated median K_{sat} (cm/hr) rates per treatment separated by block and the inter-quartile range (IQR) for the Milan location. The boxplot results for the analyzed dataset from UTRECM is shown in Figure 6. Similarly, Table 5 contains the MTREC dataset calculated median K_{sat} (cm/hr) rates and IQR of each sampled treatment (separated by block). Figure 7 shows the boxplot results for MTREC.

Soil Microbial Biomass Carbon

There were no significant differences in SMB-C estimate values across cover crop treatments at either research location (Wilcoxon/Kruskal-Wallis $P > 0.05$). Table 6 contains the mean SMB-C estimates (µg SMB C / g soil) and standard deviations for each treatment sampled at UTRECM. The boxplot results at the UTRECM location are displayed in Figure 8. The treatment means and standard deviations for MTREC are summarized in Table 7. Figure 9 shows the boxplot results of the MTREC dataset.

Table 4. Calculated medians and interquartile ranges (IQRs) for each cover crop treatment separated by block for the UTRECM K_{sat} data.

Treatment	Block	Median	IQR
NC (13)	1	2.59	5.62
	2	1.28	0.68
	3	2.04	4.62
	4	1.09	1.35
CR (8)	1	1.84	1.89
	2	10.59	18.50
	3	2.45	2.77
	4	1.46	0.66
W (6)	1	12.85	21.97
	2	1.08	0.91
	3	2.93	2.66
	4	1.04	1.91
CRCC (2)	1	1.24	5.21
	2	3.71	7.23
	3	3.67	11.23
	4	1.45	1.09
SHM (12)	1	0.65	5.12
	2	1.19	1.32
	3	2.64	10.67
	4	2.35	3.77

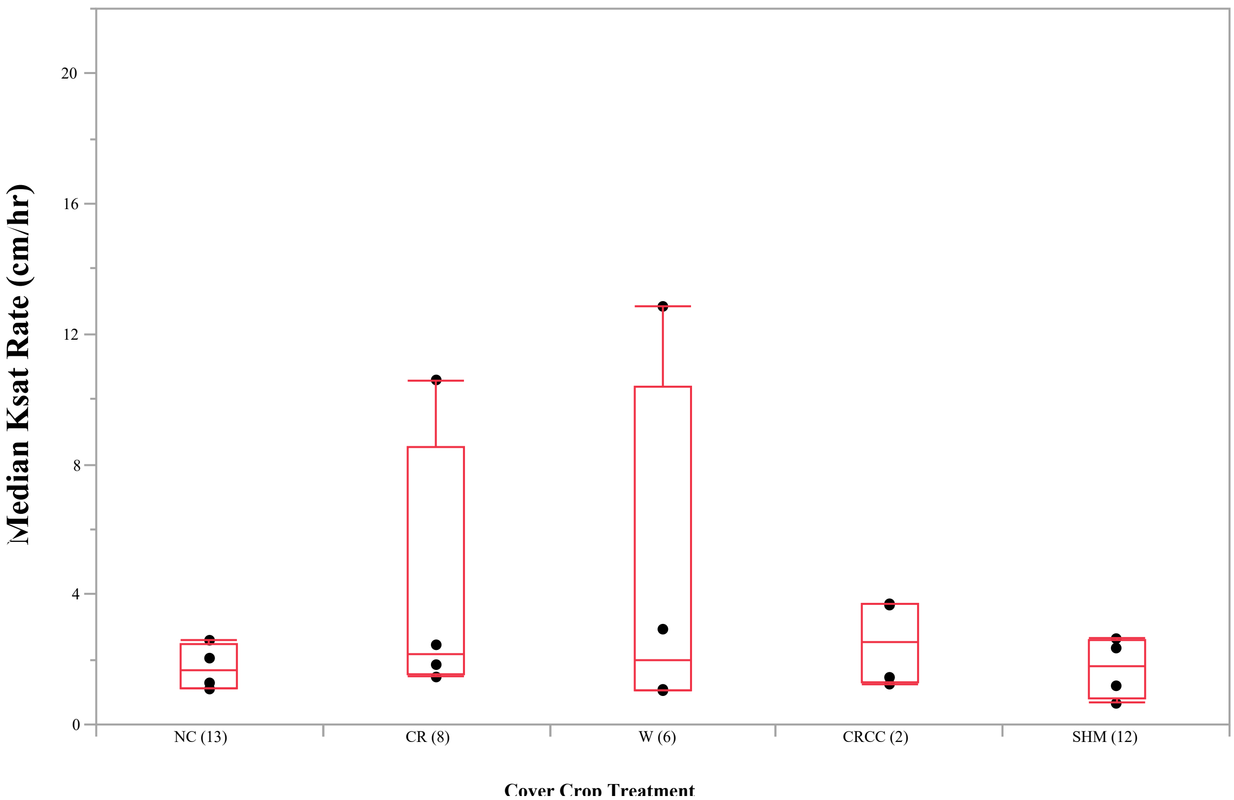

Figure 6. Boxplots of saturated hydraulic conductivity (K_{sat}) measured at UTRECM as a function of cover crop treatment: no cover (NC), cereal rye (CR), wheat (W), cereal rye + crimson clover (CRCC), and soil health mix (SHM). The black dots contained within each boxplot represent the four median block values for each treatment. The upper (75%), middle (50%, or median) and lower (25%) bounds of the boxplots display the quartiles of the treatment distribution. The lines extending from each boxplot correspond to the highest and lowest calculated median values. Wilcoxon/Kruskal-Wallis ranked sums test: Prob > ChiSq = 0.7777

Table 5. Calculated medians and interquartile ranges (IQRs) for each cover crop treatment separated by block for the MTREC K_{sat} data.

Treatment	Block	Median	IQR
NC (1)	1	4.00	2.72
	2	8.15	3.12
	3	3.26	3.75
	4	7.72	4.79
CR (2)	1	2.48	2.50
	2	5.40	6.11
	3	3.73	2.98
	4	4.48	2.97
W (3)	1	1.14	2.36
	2	1.23	0.93
	3	7.05	3.35
	4	21.29	18.46
WCC (8)	1	1.37	0.71
	2	1.82	4.67
	3	4.64	4.72
	4	4.24	3.30
SHM-A (13)	1	2.73	4.95
	2	2.82	1.19
	3	6.01	2.39
	4	6.03	2.95
SHM-B (14)	1	3.06	4.18
	2	5.64	1.51
	3	6.86	5.27
	4	2.82	3.93

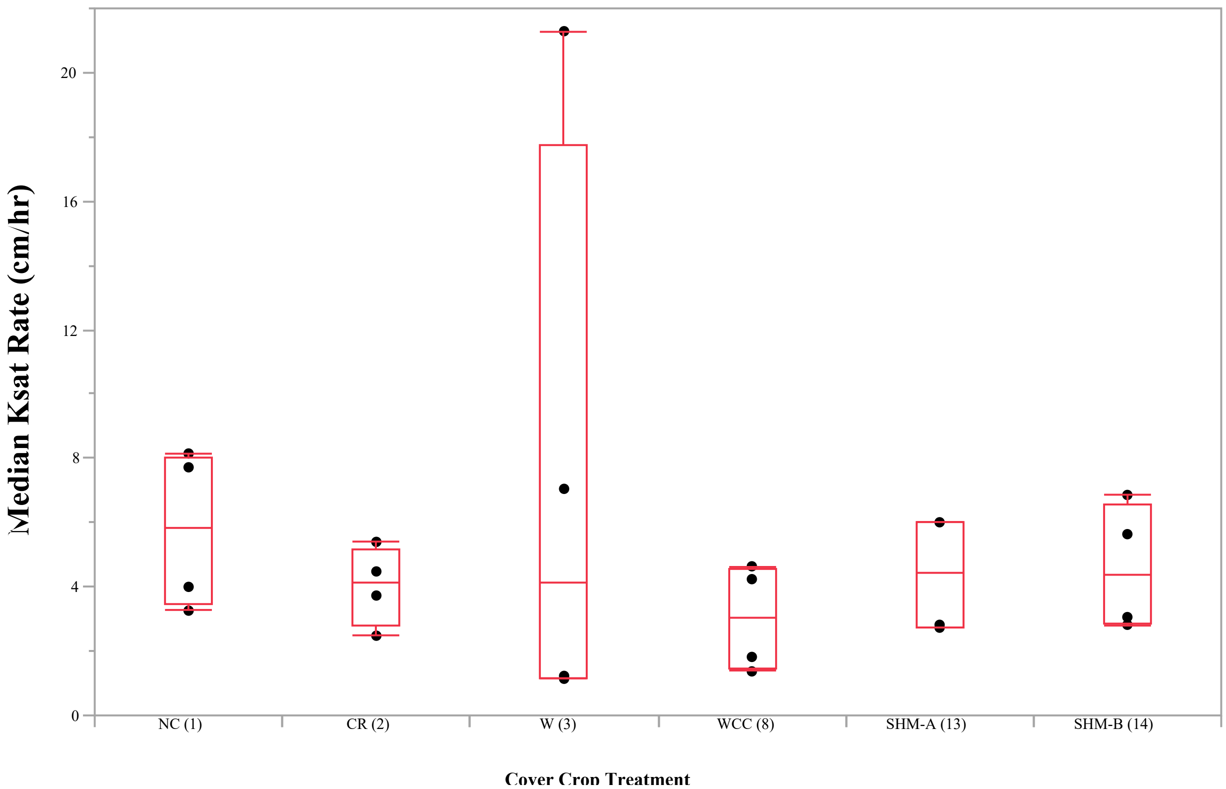

Figure 7. Boxplots of saturated hydraulic conductivity (K_{sat}) measured at MTREC as a function of cover crop treatment, no cover (NC), cereal rye (CR), wheat (W), wheat + crimson clover (WCC), soil health mix A (SHM-A), and soil health mix B (SHM-B). The black dots contained within each boxplot represent the four median block values for each treatment. The upper (75%), middle (50%, or median) and lower (25%) bounds of the boxplots display the quartiles of the treatment distribution. The lines extending from each boxplot correspond to the highest and lowest calculated median values. Wilcoxon/Kruskal-Wallis ranked sums test: Prob > ChiSq = 0.7410

Table 6. SMB-C means and standard deviations of the UTRECM data for the sampled cover crop treatments.

Treatment	Treatment Mean	Std. Dev.
CRCC (2)	259	78
W (6)	310	95
CR (8)	260	57
SHM (12)	273	106
NC (13)	293	67

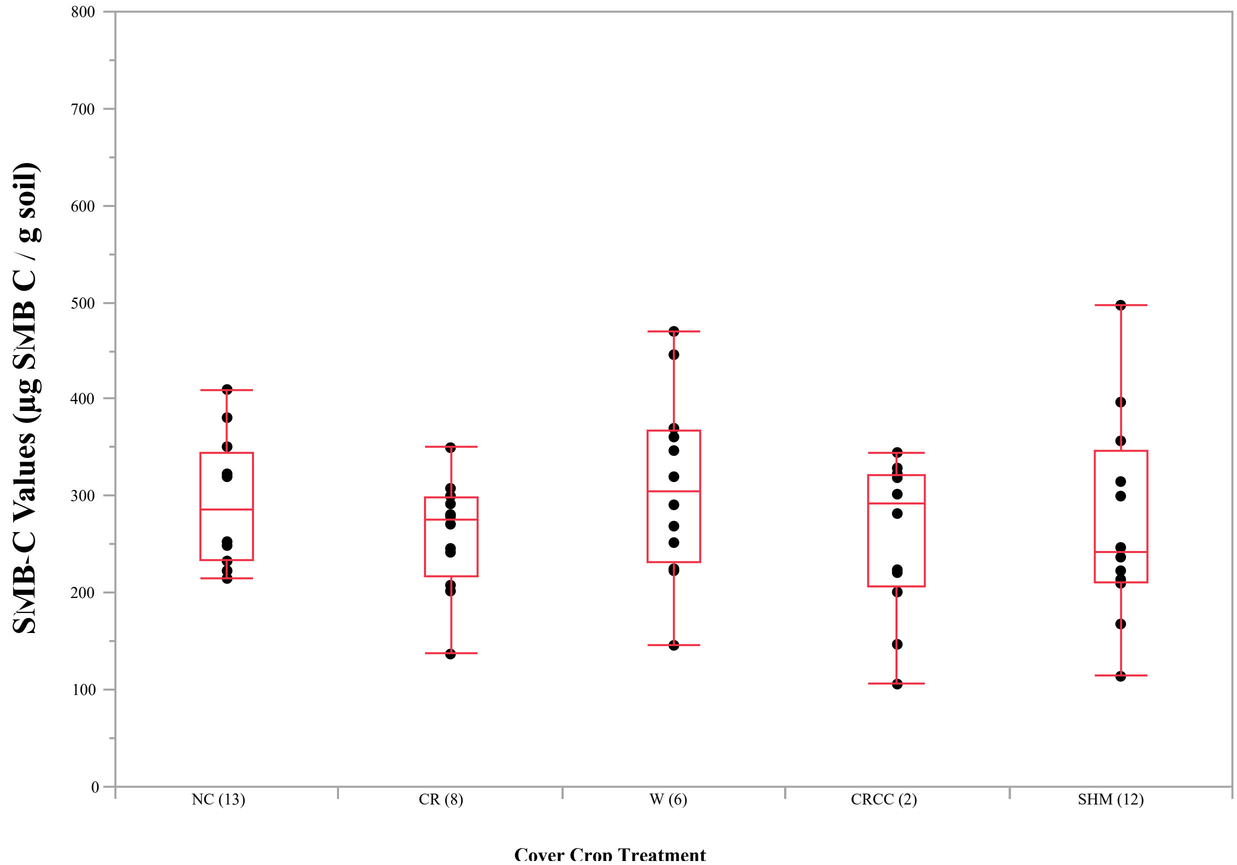

Figure 8. Boxplots of SMB-C for different cover crop treatments: no cover (NC), cereal rye (CR), wheat (W), cereal rye + crimson clover (CRCC), and soil health mix (SHM) at UTRECM. The black dots contained within each boxplot represent the 12 observations for each treatment. The red upper, middle, and lower bounds of the boxplots display the 25%, 50% (median), and 75% quartiles of the treatment distribution. Also included are the highest and lowest analyzed values for each treatment, which are represented by the lines extending from the boxplots. Wilcoxon/Kruskal-Wallis ranked sums test: Prob > ChiSq = 0.4820

Table 7. SMB-C means and standard deviations of the MTREC data for the sampled cover crop treatments.

Treatment	Treatment Mean	Std. Dev.
NC (1)	485	145
CR (2)	469	140
W (3)	494	154
WCC (8)	451	106
SHM-A (13)	431	112
SHM-B (14)	426	144

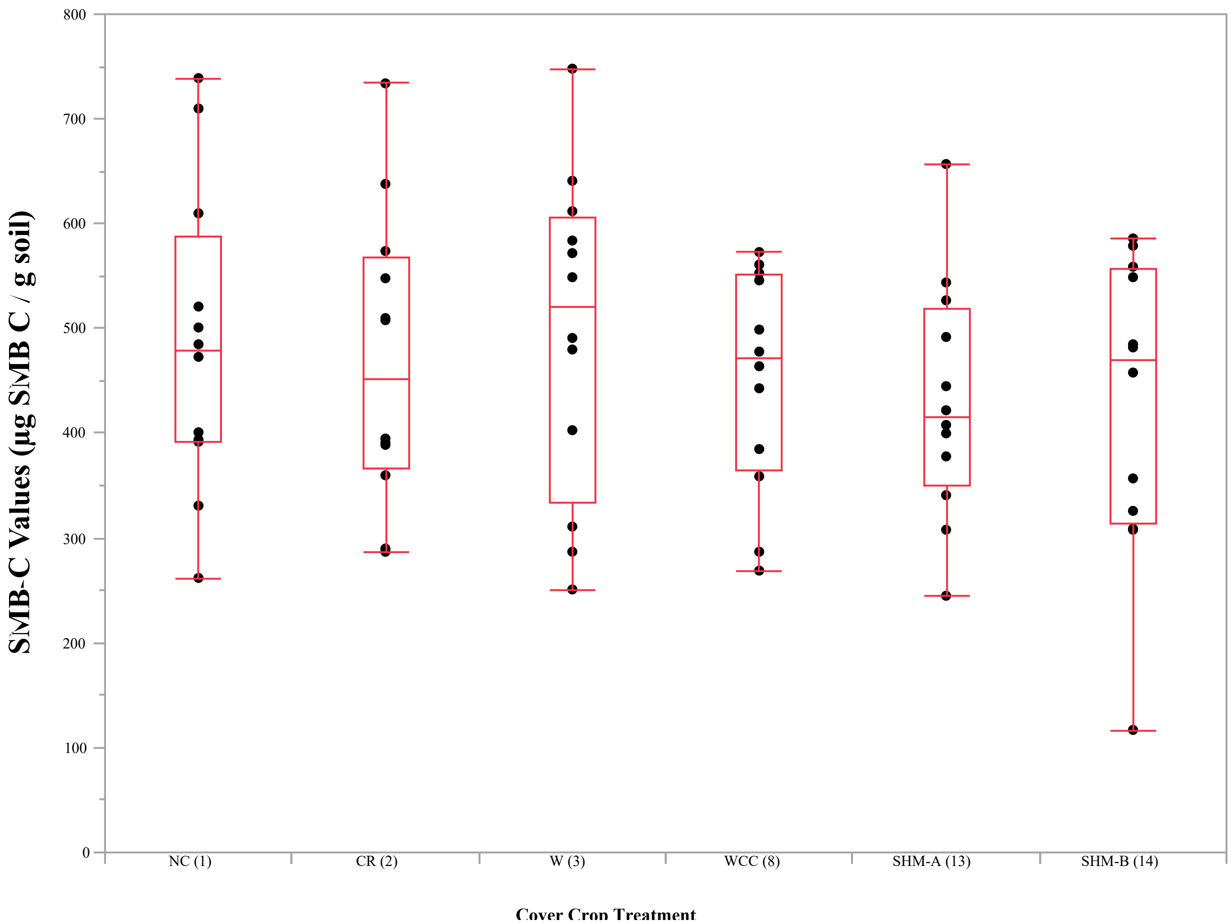

Figure 9. Boxplots of SMB-C for different cover crop treatments: no cover (NC), cereal rye (CR), wheat (W), wheat + crimson clover (WCC), soil health mix A (SHM-A), and soil health mix B (SHM-B) at MTREC. The black dots contained within each boxplot represent the 12 observations for each treatment. The red upper, middle, and lower bounds of the boxplots display the 25%, 50% (median), and 75% quartiles of the treatment distribution. Also included are the highest and lowest analyzed values for each treatment, which are represented by the lines extending from each of the boxplots. Wilcoxon/Kruskal-Wallis ranked sums test: Prob > ChiSq = 0.8299

DISCUSSION

Diverse Crop Rotations

Continuous cropping or growing the same crop year after year rather than in a typical rotation, has been shown to have detrimental effects such as increases in weed, pest, and crop disease cycles, which can result from a lack of crop rotation (Huggins and Reganold, 2008). Poor yields and crop failures, which can result from continuous cropping, are not desired by producers. Crop rotations, such as corn-soybean rotations, provide a simple and effective management practice to alleviate problems associated with continuous cropping (Huggins and Reganold, 2008). Incorporation of one or two additional crops into the rotation provides even better effects (Pakeman et al., 2019). Growing the same crop in the same place year after year makes it more difficult for weeds, pests, and diseases to negatively impact crops (Pakeman et al., 2019). There are additional benefits of diverse crop rotations, such as enhancing soil carbon (C), nitrogen (N), and microbial biomass (SMB) (McDaniel et al., 2014). Ashworth et al. (2017) reported yield increases when the diversity of rotation was increased.

Crop Residues

The USDA suggests the general rule that "soil should be covered whenever possible" (2020). This principle is a foundation of cover crop and increased residue practices. An easy way to increase soil cover is to simply leave the dead plant residue in place. This is possible when tillage is ceased or drastically reduced. Using plant residues or cover crops (living residues) as a means of soil cover is listed as a "strategy for improving soil health" by Magdoff (2001). Tisdale et al. (1984) states that crop residue is “the greatest source of soil organic matter.” Weed suppression is an additional benefit of leaving crop residues in place (Barnes and Putnam, 1983).

Organic Mulches

Shojaei et al. (2019) defines mulch as “a thin layer which is placed on the soil surface and preserves soil, water, and plants.” Mulches can be separated into two descriptive or functional types such as organic mulches (crop residues, plants, manures, straw, leaves) and inorganic mulches (sand, rubber mulch, plaster, cement) (Shojaei et al., 2019). Organic mulches are commonly included in practices designed to increase or sustain soil health (Abawi and Widmer, 2000). These organic mulches can be applied in several different methods depending on the type of mulch being used and amount to be applied, such as by hand or using hand tools for small areas or by mechanical means for larger scale operations.

Earthworms

At UTRECM, Storck (1996) observed statistically significant differences in earthworm populations over time in both conventional and no-till treatments as well as with cover crop treatments. When the soil structure remained undisturbed, earthworms reached an equilibrium, resulting in a carrying capacity for a given area and hence providing a field scale tapestry of preferential pathways for precipitation or irrigation water to infiltrate into the soil profile. Storck (1996) presents results indicating that the earthworms can begin their processes of building the network of tunnels as soon as one year after tillage is ceased. The trend of increased earthworm populations continues to statistically increase at five years after cessation of tillage but then diminishes in significance at ten years, though the earthworm counts continued to get larger. Both UTRECM and MTREC, where the research plots for this study were located, had been under no-till management for more than two decades prior to sampling initiation. It is likely that the extensive preferential flow pathway produced by the earthworm burrows over-rode the influence that the different cover crops might have had on infiltration rates.

Tillage is not the only factor known to affect earthworms on the landscape. Hubbard et al. (1998) concluded that crop rotation can significantly impact earthworm populations. Hubbard et al. (1998) determined that earthworm populations were higher in corn-soybean rotations than in wheat-corn rotations, due to the differences in crop residue quantity and quality. Abail and Whalen (2018) observed statistically significant results for earthworm populations as an effect of surface residue quantity. Differences of nearly double population counts for earthworms has been identified across high and low corn stover residue treatments (Abail and Whalen, 2018). Abail and Whalen (2018) also propose that the half-life of corn residue (nearly 200 days) is beneficial to earthworms by providing a long-term food source. This is contrasted by the transient nature in which earthworms use soybean residues, which only has a residual half-life of about 24 days (Abail and Whalen, 2018).

Ashworth et al. (2017) observed statistical differences in earthworm populations among crop rotations at UTRECM when rotations of continuous cotton, continuous corn, continuous soybean, cotton-corn, and corn-soybean are evaluated. Populations were significantly lower under continuous cotton compared to systems with corn or soybeans in the rotation. Ashworth et al. (2017) also concluded that biocovers, such as poultry litter, can also significantly impact earthworm populations at UTRECM and MTREC. Katsvairo et al. (2007) identified significant differences in earthworm populations in a cotton-peanut (*Archais hypogaea* L.) rotation containing two years of bahiagrass (*Paspalum notatum* Fluegge) prior to planting cotton compared to a typical cotton-peanut-cotton-cotton rotation. Earthworm populations were different under different irrigation treatments, which signifies the importance of soil moisture to earthworms.

Statistically significant differences in infiltration rates based on crop rotation is also presented by Katsvairo et al. (2007). Rotations which included a bahiagrass treatment averaged almost a ninefold increase compared to the conventional rotation of cotton-peanut-cotton-cotton (Katsvairo et al., 2007). Infiltration rates in peanut treatments which followed twelve years of bahiagrass and switchgrass (*Panicum virgatum* L.) provided infiltration rates which were sevenfold higher compared to the other treatments (Katsvairo et al., 2007). Katsvairo et al. 2007 presents regression analysis which includes R^2 values of 0.92 ($P \geq 0.0086$), and 0.99 ($P \geq 0.0091$) and a therefore positive correlation between earthworm populations and infiltration rates.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATION

CONCLUSIONS

The prevalence of pathways created by the earthworms seems to negate any ability to quantify possible cover crop treatment impacts to infiltration because the earthworm channels provide the pathway for preferential flow of water being infiltrated. The UTRECM and MTREC sites were long-term (20+ years), no-till, had cover crops, intentionally left crop and cover crop residues on the landscape, and were managed under typical corn-soybean rotation protocols. This management system promoted soil health and benefited earthworm populations, creating preferential pathways for water infiltration and soil microbial biomass, and is the probable explanation as to why there were no significant differences for neither the K_{sat} rates nor the SMB-C values among the cover crop treatments at either location despite the temporal variance. A possible explanation for the difference in magnitude of SMB values across locations is the production crop that was being grown on the landscape. When samples were collected, MTREC had corn planted and UTRECM was planted with soybeans. The crops at both locations were well into maturity when soil samples were taken. The additional nitrogen applied at MTREC (recommended for corn by soil test) may be responsible for the value differences across locations for the SMB-C data. Similarly, slight climate differences between locations may have had an impact on potential soil moisture given that UTRECM is typically drier than MTREC and soil moisture is shown to be a primary driver of soil microbial biomass.

RECOMMENDATION

In retrospect, it is thought that future experimental designs should include tilled ground, initiating no-till sequence which would be split-plotted with cover crop treatments to truly evaluate the cover crop treatment effects adjacent to and apart from long-term no-till practices. It is more than likely that after a certain time period, possibly five years, that the natural pathways created in the no-till plots without cover crops would begin to narrow in significant difference from any cover crop treatments due to the equilibration of earthworm population carrying capacities. Establishing such plots would also allow researchers to identify which of the commonly used cover crops would be best suited to improve soil health during the transition to no-till and/or which cover crop treatments perform best in the conventional tillage plots to assist producers in improving soil health or even individual soil physical properties. All of this information would be beneficial in identifying methodologies to help producers adapt to climate change issues.

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VITA

Adam Allen Zimmerman was born in Neenah, Wisconsin in 1980. He is the oldest of three boys: his brothers Corey and Brandon. Parents, Allen and Kathleen Zimmerman, moved the family to Murfreesboro, Tennessee in 1983. Adam attended Hobgood and Black Fox Elementary Schools, Central Middle School, and graduated from Oakland High School in May 1999. Adam joined the United States Navy following September 11, 2001 and received an Honorable Discharge in October 2004 after being injured in training. Adam moved to Knoxville, Tennessee in August of 2007 and sought training in Fire and Emergency Services from various entities. He honorably served the public as a full-time firefighter/paramedic from 2007 to 2014, when he decided to fulfill his lifelong goal of a college degree in science. With the support of his gracious wife, Natalie, Adam enrolled in Roane State Community College in August 2014 and earned an Associates of Science in May 2016. Adam enrolled at the University of Tennessee, Knoxville in June 2016 and earned his Bachelor of Science degree in Environmental and Soil Science with a concentration in Soil Science in December 2018. He immediately began his graduate work at the University of Tennessee, Knoxville and accepted a Graduate Research Assistantship. Adam also worked as a teaching assistant for Dr. Neal Eash, who taught Soil Fertility and Nutrient Management. Adam earned his Master of Science degree in Environmental and Soil Science and graduated in August 2021. Gratitude and appreciation are not strong enough words to embody his feelings for all who were involved in his educational journey.