Winter Cover Crop Performance in the Southern Piedmont Region of South Carolina

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WINTER COVER CROP PERFORMANCE IN THE SOUTHERN PIEDMONT
REGION OF SOUTH CAROLINA

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Plant and Environmental Science

by
Payton Brie Davis
May 2023

Accepted by:
Dara Park, Committee Chair
Aurelie Poncet
Brook Russell
Debabrata Sahoo
ABSTRACT

Cover crops (CC) offer in-field and environmental benefits when integrated into cropping systems. Low CC adoption in the southern Piedmont of South Carolina is partially due to the lack of information on CC performance and benefits within the region. To address this, eight winter CC and a fallow/pigweed treatment were investigated for their influence on soil temperature, volumetric water content (VWC), percent cover, biomass, and the occurrence of soil water repellency (SWR). A randomized complete block design experiment was conducted in the fall and winter of 2021-2022 (EXP A) and repeated in 2022-2023 (EXP B). Cover crops minimally influenced soil VWC over both experiments with no consistent trend. Cover crops did not influence soil temperatures during EXP A. In EXP B, soil under fallow/pigweed had the highest soil temperatures on two (out of ten) measuring events (ME) (P < 0.05). No SWR was found in either experiment. Establishment, and fresh and dry CC biomass was influenced by rainfall directly before and after seed planting. Regardless of rainfall, annual rye produced cover quickly and yielded high biomass. The crimson clover took longer to establish, but also yielded one of the highest biomasses. This study demonstrated that CC had little influence on soil physical properties and that while cereal rye is a common CC utilized for erosion control, the greater biomass and surface roots of annual rye make it a superior cover crop for use in the Southern Piedmont agroecosystems.
ACKNOWLEDGMENTS

I would like to sincerely thank my committee members for their guidance and expertise throughout this project. I thank Dr. Park for her encouragement, faith, and investment in me. She always went the extra mile to make sure I was prepared for any presentation and always offered a helping hand in the lab and in the field. I thank Dr. Russell for always finding time to meet with me and helping me with the statistical analyses. Our meetings were extremely helpful. I would also like to thank my other committee members Dr. Poncet and Dr. Sahoo for their valuable feedback, support, and the perspectives they brought to the project. I am extremely grateful for all my committee members and their mentorships.

I am also extremely grateful for Brad Stencil and the field crew at the Calhoun Fields for preparing the land where this project took place. This project would not have been the same without their help.

Finally, I want to thank my parents, Tammy and Stewart Davis, and my brother Colton Davis for their endless support and encouragement throughout this journey.
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CHAPTER ONE
INTRODUCTION

Cover Crops Benefits and Adoption

The benefits of cover crops (CC) have been widely documented dating back 3000 years ago to the Chou Dynasty, in which clovers were used as a CC to improve the productivity of the soil by supplying nutrients to the cash crop (Pieters, 1927). Cover crops are defined as a crop that is planted in between times of cash crop production (SSSA, 1997). Cover crops are not harvested. They are terminated and left in the field to decompose (Bergtold et al., 2017). The decomposing plant matter releases nutrients that the subsequent cash crop can utilize. Other benefits from CC include protecting from soil erosion (Dabney et al., 2001, Blanco-Canqui, et al., 2015, and Lu, et al., 2000), enhancing different soil properties (reducing bulk density, improving aggregate stability, balancing pore ratio (Blanco-Canqui et al., 2015), scavenging nutrients (Snapp et al., 2005 and Cooper, et al., 2017), weed suppression (Bergtold et al., 2017, and Adetunji, et al., 2020) and pest management (Sharma et al., 2018 and Snapp et al., 2005).

Cover crops protect soil from rain erosion by intercepting rain droplets, and reducing the velocity of the rain when it reaches the soil (Dabney et al., 2001). With a decrease in velocity, there is less force to dislodge the soil particles. Cover crops, especially ones with fibrous root systems help to anchor in soil, protecting the soil from concentrated flow erosion (Baets et al., 2011). For example, winter rye (Secale cereale L.) grown in Clemson South Carolina in an Ultisol soil (Bilbro 1991) and winter triticale (x Triticosecale Wittm.) grown in the semiarid central Great Plains in a Ulysses silt loam
soil (Blanco-Canqui et al., 2013) reduce soil loss by water and wind erosion. Cereal rye and oats effectively scavenge and cycle nutrients, thus reducing nitrogen loss. In Iowa, cereal rye (Secale cereal L.) and oats (Avena sativa L.) were both found to reduce nitrate losses in drainage water (Kaspar et al., 2012). Another two-year study conducted in California documented that nitrogen leaching through the soil was reduced by >50 kg ha$^{-1}$ N when CC mixtures were grown as part of a vegetable crop production (Jackson et al., 1993). Decomposing CC residues offer nutrients to support cash crop growth (Schipanski et al., 2014). Legumes in particular aid in supplying nutrients by creating a symbiotic relationship with bacteria in the rootzone to fix nitrogen in plant available forms (Blanco-Canqui et al., 2015).

Cover crops can help suppress weeds by a few mechanisms. Cover crops in the Brassicaceae family suppress weeds (as well as some soil-borne pathogens) by releasing biofumigants (Baysal-Gurel 2019). Other CC suppress weeds by covering the soil (Schipanski et al., 2014). When CC have greater soil cover, they can shade out the weeds, making it harder for weeds to grow and compete. Cover crops can help suppress weeds by affecting nitrogen availability within the soil (Schipanski et al., 2014). For example, cereal rye in a no-till soybean system can immobilize nitrogen, limiting nitrogen availability and subsequently decreasing the biomass of pigweed (Williams et al., 2018).

Cover crop benefits are dependent on the type of CC planted, the soil type, management systems, and climate (Blanco-Canqui et al., 2015, Miner et al., 2020 and Tonitto et al., 2006). Cover crops that work well in one region may not work well in another region due to differences in soil type, and climate (Cates et al., 2018). For
example, in the mid-west U.S., tillage radishes are used to penetrate subsoils. However, there have been anecdotal observations of the radish being unable to penetrate through the dense clay subsoils in the Southeast U.S. Instead, the radish starts to grow above the soil surface. In fields where this happens, the radishes are instead grown for biomass accumulation.

The USDA Economic Research Service identified that CC use is highest in the eastern and southern United States (Hamilton et al., 2017). However, the use and adoption of CC remains low as adoption is less than 30% in the southern United States (Hamilton et al., 2017). Lamichhane and Alletto (2022) explained that the poor adoption of CC is due to knowledge gaps in management. South Carolina’s environmental conditions offer long cropping seasons, making the state ideal for growing winter CC (St Anime et al., 2020). Cover crops grown in South Carolina include cereal rye (Secale cereale), ryegrass (Lolium spp.), oats (Avena sativa), wheat (Triticum spp.), sorghum sudangrass (Sorghum x drummondii), and crimson clover (Trifolium incarnatum) (Clay et al., 2020). A recent survey study conducted in South Carolina showed that more farmers have adopted cover cropping in recent years but adopting CC remains to be a challenge for farmers (Clay et al., 2020). Reasons for the slow adoption include the price of seeds, seed availability, and the cost of planting and terminating CC (Clay et al., 2020).

**Soil Water Repellency**

Defined as the reduction in wetting and water retention of soil, SWR is when soil surfaces resist water. The impact of a water repellent soil begins with water entering and
moving through the soil where there is no SWR, creating and affecting the preferential flow pathways. This nonuniformity of water infiltration and hydraulic conductivity throughout a soil’s profile can result in standing water on the soil’s surface, and/or water lost as runoff (Doerr et al., 2000). Nonuniform soil moisture within the rhizosphere created by a preferential flow can result in poor seed germination, and stressed plants that may have decreased quality and yields (Roper, 2005). Preferential flow pathways result in deep leaching of water and chemicals carried within the soil solution (e.g., fertilizers and pesticides) past the rootzone and can lead to potential contamination of natural resources (Doer, et al., 2000). It is also important to note that the environmental conditions in the southeastern United States are optimal for microbial decomposition. This makes it difficult to build up soil organic matter (Magdoff & Es, 2021).

The potential for rapid loss of easily degradable plant components (Magdoff & Es, 2021) and the build-up of residues that are primarily comprised of water repellent plant components (Mao et al., 2015), the extreme wetting and drying cycles that are becoming more prevalent (Hallett, 2007), and the natural sandy loam and loamy sand textured surface soils (Woche, et al., 2005) are a trifecta for SWR to become a problem in the southeastern United States. Soil water repellency has been documented in many native and constructed soils including soils under the forest that have been burned (Malkinson and Wittenberg, 2011) and soils within a golf course (York and Canaway 2000). Soil water repellency has been documented in agricultural systems including potatoes (Robinson, 1999), maize (Markus et al., 1994, Urbanek et al., 2007), wheat (Markus et al., 1994, Urbanek et al., 2007), citrus orchards (Cerdà and Doerr, 2007),
However minimal research has looked at SWR in row cropping systems (especially in the Southern U.S.) and how CC may impact the development and occurrence of SWR. Overall adoption of CC remains low, especially in the southern Piedmont region of South Carolina. Lack of knowledge on CC performance within this region is a main reason for the low adoption rate (Lamichhane & Alletto, 2022). The objective of this study was to collect data on the performance of CC in the southern Piedmont of South Carolina and on the effects on soil physical properties including soil temperature, percent coverage, volumetric water content (VWC), and soil water repellency (SWR) throughout the growing season of the CC, and biomass at the time of CC termination. Having a baseline knowledge of winter CC performance, their effects on soil physical properties, and how they may influence the development and/or alleviation of SWR within the Southern Piedmont will help farmers make informed decisions on integrating CC into their rotations. The null hypothesis of this experiment was that the CC treatments will perform similarly on each measuring event (ME). The alternate hypothesis is that different CC treatments would have different performances on each ME, including differences in soil temperature, soil VWC, percent cover, SWR, and biomass.
CHAPTER TWO
METHODS AND MATERIALS

Site and Establishment

A field-scale experiment was initiated on 25 August 2021 and ended on 02 March 2022 (EXP A) and repeated on 14 September 2022 and ended on 06 March 2023 (EXP B) at Calhoun Fields, a fields research farm on Clemson University’s campus in Clemson, South Carolina (34.67616°N, 82.83517°W) (Figure 2.1). The field soil series is Toccoa, and the taxonomic class is Coarse-loamy, mixed, active, nonacid, thermic Typic Udifluvents. It has a sandy loam surface with a fine sandy loam subsoil (Soil Survey Staff).

Both experiments were conducted as completely randomized block designs to examine eight CC commonly grown in the region and a fallow/pigweed treatment (Table 2.1) with three replications. The annual ryegrass, crimson clover, oats, mustard, radish, and medium red clover seeds were sourced from Saddle Butte Ag (Shedd, Oregon) (Table 2.1). Hairy vetch was sourced from Cameron Mills (Walton, Indiana) (Table 2.1). In EXP A, the cereal rye seeds never germinated. In EXP B, a different source (Moore Seed Farm, Elsie, Michigan) of cereal rye seed was included. Experiment A had a total of 24 plots within the study (8 treatments, 3 replications) (Figure 2a). Experiment B had a total of 27 plots within the study (9 treatments, 3 replications) (Figure 2b).

The field history includes growing primarily corn and soybean as well as other row crops for research purposes. Seedbed preparation included disc tillage to remove any weeds and corn stalks. Each CC was hand seeded into a 1.8 by 1.4-meter plot (Figures 2a
and 2b). To mimic broadcasting, CC were shaken out of the hand in a horizontal, vertical, and diagonal pattern from the north and south sides of a plot. Each plot was separated by a 0.3 m alley that was kept clear of weeds by using a garden hoe (Wood-Handle Action Hoe, Craftsman) (Figures 2a and 2b). Weeds were hand pulled in the CC plots until the CC were established (defined as 80% cover). Weeds were not removed from fallow/pigweed plots.

**Data Collection**

Once the CC were fully established in EXP A (November 2nd, 2021), VWC, percent coverage, and soil temperature readings were taken every other week until termination on March 2nd, 2022. In comparison, not all the CC reached full establishment in EXP B. Starting November 22nd, 2022, VWC, percent coverage, and soil temperature readings were measured every other week until termination on March 6th, 2023. Volumetric water content and soil temperature were measured using the FieldScout TDR 150 soil moisture meter (Spectrum Technologies, Inc., Aurora, Illinois). Percent coverage was measured visually by the first author (Buchi 2018).

Soil cores were collected every two weeks from each plot using a 10 cm diameter soil corer (33" Plated Step Probe, AMS, American Falls, ID) to a depth of 12 cm (representing majority of the rootzone) where SWR has been found to be most extreme (Dekker et al., 2001 and Ritsema, et al., 1998). The Water Drop Penetration Time method (Dekker et al., 2009) was used to measure SWR on freshly collected core samples at 0,1,2,3,4,5,6,8,10, and 12 cm depths. Cores were brought back to the lab to air dry for two weeks at which time the measurements were conducted again (Kostka et al., 1997).
The first cores were collected January 10th, 2022 for EXP A as the author’s original thoughts were that it would take time for CC root exudates to contribute to SWR. When no SWR was determined, the authors decided to monitor for SWR earlier in the following experiment (EXP B-November 29th, 2022).

Biomass was collected by placing a 0.25 m² polyvinylchloride pipe quadrant in an area of the plot that best represented growth of the whole plot. Aboveground biomass was removed using hand shears (19.05 cm gardening shears). The cut biomass was placed in a marked brown bag and weighed (EJ-6100 Compact Balance, A & D, Ann Arbor, Michigan) for fresh weight. The biomass was brought back to the lab where the samples were dried (414004-552 VWR Symphony Gravity Convection Oven, VWR, Radnor, Pennsylvania) at 60 °C for 48 hours to stop decomposition (Hodgdon, et al., 2016). After the samples were dried, the biomass was reweighed (dry biomass). Below ground biomass was also collected for radish because of their large underground biomass. In both experiments, the radishes were harvested when the top growth senesced since they are not winter hardy (November 2nd, 2021, and January 2nd, 2023, for EXP A and B respectively). In EXP B, oats and mustard were harvested earlier than the other winter hardy CC as the aboveground growth was dying off with no new growth.

Daily rainfall and mean air temperature were obtained from the Clemson University weather station (0 34.679° N, 82.843° W) located approximately 740 m from the study field. All rainfall events greater than 2.5 mm per day were considered.

Statistical Analysis
Statistical analysis was performed in JMP (JMP Pro 16, SAS Institute Inc., Cary, North Carolina). Shapiro-Wilk goodness-of-fit test was used to test whether it was reasonable to believe that errors were normally distributed. In addition, Normal Quantile Plots were analyzed to further assess this Normality assumption. The equal variance assumption was assessed by visually inspecting residual plots. If it was determined that assumptions regarding the distribution of the errors were not reasonable, power transformations of the response variable were considered, where the Box-Cox procedure was used to determine the optimal transformation.

EXP A and EXP B had eight and nine CC treatments respectively, with three blocks (random variable). The main effect of ME was assigned as a continuous variable. A mixed model was first explored that included EXP as a main effect and as part of an interaction effect with BLOCK, CC, and ME. The model identified that both EXP and ME were highly significant ($P < 0.0001$). When a mixed model was conducted for each EXP, ME was determined as highly significant ($P < 0.0001$, Table 2.2). Thus, a model was conducted for each ME testing CC, BLOCK and CC*BLOCK. Since biomass was only measured at time of termination, a different model was constructed with EXP, CC, and BLOCK and CC*EXP as main factors. Since EXP was significant, the model was adjusted to test each EXP separately (Table 2.3). When CC treatment was significant, Tukey’s honestly significant difference (HSD) was used for pairwise comparison of treatment means. All test were performed using the 0.05 significance level. All inferences are based on the untransformed data unless otherwise noted.
Tables and Figures

Table 2.1. Summary of Cover Crops Grown and Seeding Rates.

<table>
<thead>
<tr>
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<th>Scientific name</th>
<th>Variety</th>
<th>Rates (kg h(^{-1}))</th>
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<td><em>Lolium multiflorum</em></td>
<td>Bounty</td>
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<td>Cereal Rye</td>
<td><em>Secale cereale</em></td>
<td>Wheeler Rye</td>
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<td>Crimson Clover</td>
<td><em>Trifolium incarnatum</em></td>
<td>Dixie</td>
<td>25.0</td>
</tr>
<tr>
<td>Hairy Vetch</td>
<td><em>Vicia villosa</em></td>
<td>TNT</td>
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<tr>
<td>Oats</td>
<td><em>Avena sativa</em></td>
<td>VNS</td>
<td>158.4</td>
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<tr>
<td>Medium Red Clover</td>
<td><em>Trifolium pratense</em></td>
<td>VNS</td>
<td>19.8</td>
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<tr>
<td>Mustard</td>
<td><em>Brassica juncea</em></td>
<td>Shield</td>
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<td>Radish-Daikon</td>
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<td>Enricher</td>
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<td><em>Longipinnatus</em></td>
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Table 2.2. Degrees of freedom (df) and significance for main effects and factor interaction on volumetric water content (VWC), soil temperature, and percent cover.

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<td>$F$</td>
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Table 2.3: Degrees of freedom (df) and significance for main effects on fresh and dry biomass. Note, the results for EXP A dry biomass and EXP B fresh and dry biomass are transformed via natural logarithm.

<table>
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<tr>
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Figure 2.1: The winter cover crops (CC) were grown in the Calhoun Fields located in Clemson, South Carolina. The triangle represents where the weather station was.
Figure 2.2. Plot plan for (a) 2021-2022 (EXP A) and (b) 2022-2023 (EXP B) where each cover crop (CC) treatment is in a 1.8 by 1.4-meter plot. AR: Annual Rye, CR: Cereal Rye, CC: Crimson Clover, F/P: Fallow/Pigweed, HV: Hairy Vetch, M: Mustard, O: Oat, R: Radish, RC: Red Clover. Block 1: No shading, Block 2: Light grey shading, Block 3: Dark grey shading.
CHAPTER THREE
RESULTS AND DISCUSSION

Weather

Daily mean temperatures over EXP A were similar to the 2017 to 2021 5-yr average mean temperatures (14.3°C and 14.4 °C for EXP A and 5-yr average respectively), (Figure 3.1a). Total rainfall during EXP A was 26.1 cm compared to 69 cm for the 5-yr average (Figure 3.1a). During EXP A there were less rain events than determined during the 5-yr average (22 and 43 events for EXP A and 5-yr average respectively), (Figure 3.1a). The beginning of EXP A was dry and most rain occurred during December through February (Figure 3.1a). The average rainfall was less per event for EXP A compared to the 5-yr average (11.94 and 16 mm event⁻¹, respectively) (Figure 3.1a).

Mean daily temperatures over EXP B were similar to the 5-yr average mean temperatures (12.8 and 12.6 °C for EXP B and 5-yr average respectively), (Figure 3.1b). Total rainfall during EXP B was 47.3 cm compared to 65.9 cm for the 5-year average (Figure 3.1b). During EXP B there were less rain events than the 5-yr average (34 and 40 events for EXP B and 5-yr average, respectively). The average rainfall was less per event for EXP B compared to the 5-yr average (13.97 and 16.26 mm event⁻¹).

The mean temperatures during EXP A were warmer than the mean temperatures during EXP B (14.3 and 12.8 °C for EXP A and EXP B, respectively). The total rainfall during experiment A was less than the total rainfall for EXP B (26.1 and 47.3 cm for EXP A and EXP B, respectively). The average rainfall of EXP A per event was less than
the average rainfall per event of EXP B (11.94 and 13.97 mm event\(^{-1}\) respectively). Even though EXP B had more rain, EXP A had some rainfall (0.254 mm) within a day of planting which helped with seed emergence. EXP B did not receive any rain till 12 days after planting.

**Soil Volumetric Water Content**

The permanent wilting point (PWP) and field capacity (FC) of the soil is 0.067 cm\(^3/cm^3\) and 0.164 cm\(^3/cm^3\), respectively (Soil Survey Staff). For EXP A the mean VWC of each treatment was never below the PWP at any measuring event, and every treatment was above the FC seven out of 12 measuring events (Table 3.1). The mean soil VWC of each treatment during EXP B was never below the PWP at any measuring event and above the FC on nine out of ten measuring events. For both experiments, soil VWC increased or decreased dependent on rainfall over the previous week. For example, when there is greater rainfall within the previous week (ex. Week of Jan. 3rd), soil VWC was greater (Figure 3.1a, Table 3.1). When there is little to no rain the previous week before a measurement event, (ex. week of Nov. 30th), soil VWC was lower (Figure 3.1a, Table 3.1).

Soil VWC was different under CC on three measuring events during EXP A (Table 3.1). On November 18th, the VWC of fallow/pigweed treatment was greater than the VWC under mustard and oat treatments, and similar to all other treatments. On December 7th, the VWC of the fallow/pigweed and red clover treatments was greater than the VWC under the oat treatment, and similar to all other treatments. On March 3rd, soil under the fallow/pigweed treatment, hairy vetch and red clover had a greater VWC.
than under mustard and radish treatments. For each of these three measuring events, rainfall was less than 0.05 cm for the previous week.

During EXP B, CC treatments influenced the mean soil VWC on five measuring events (Table 3.2). On November 29th, the soil VWC under the mustard treatment was greater than the VWC of the crimson clover treatment, with both being similar to all other treatments. On December 13th, the soil under the fallow/pigweed treatment once again had the highest VWC, being significantly greater than the hairy vetch, mustard, crimson clover, and radish treatments. On December 20th, a greater VWC was measured under the fallow/pigweed treatment in comparison to the crimson clover and mustard treatments. On February 14th, soil under cereal rye had a greater VWC than the fallow/pigweed treatment. On February 28th, cereal rye had a greater VWC than the radish treatment. Unlike EXP A, the weekly rainfall accumulation was not consistently low on measuring events when CC influenced soil VWC. Instead, the weekly rainfall accumulation when the soil VWC was different varied from 1.2 cm to 5.5 cm.

On the majority of measuring events during EXP A, and EXP B, the CC grown did not impact soil VWC. This is consistent with a study conducted in Iowa and Indiana where in two out of three fields the soil VWC under a corn-soybean rotation during extremely dry conditions following termination of the rye CC was similar to where no CC was grown (Daigh et al., 2014). On measuring events when CC treatment influenced soil VWC, having the fallow/pigweed cover resulted in the highest soil VWC in EXP A for all three measuring events and two out of five measuring events in EXP B in which CC treatment influenced soil VWC (Tables 3.1 and 3.2), albeit that it was statistically
similar to many other CC treatments. A long-term study in Kansas identified that late-maturing soybean (Glycine max) and sunn hemp (Crotalaria juncea) used as two different summer CC, resulted in 35% greater soil VWC compared to plots without CC (Blanco-Canqui et al., 2011).

Perhaps when water within the soil is not being replenished by precipitation (in this case, rainfall), different CC species use water at different rates resulting in different VWC. Silva (2014) found that volumetric water content varied under different species of CC (hairy vetch, Austrian winter peas, winter rye, winter barley, and winter triticale) in an organic no-till system in Wisconsin. Similar to the results of EXP A, a two-year study conducted in southwestern France documented that for months in which less than 50 mm of total rainfall occurred during the first year of the experiment, soil water content under the bare soil was greater than soil under the CC mixture of Ethiopian mustard (Brassica carinata) and crimson clover (Trifolium incarnatum) (Meyer et al., 2020). Other factors may also complicate how CC influence soil VWC. For example, a conventional tillage system with a winter fallow reduced the VWC more than a no-till system with rye CC and a no-till system with a mixed species CC in a Texas field used to produce cotton (Burke et al., 2021). The amount of biomass production is also thought to influence the impacts CC have on soil VWC (Daigh et al., 2014). Daigh, et al., (2014) documented that when there is minimal difference between the above ground biomass of the living CC, the soil VWC is not significantly different. However, when there is a large difference in the above ground biomass, differences in soil VWC may be present.
Soil Water Repellency

There was no SWR found in EXP A or EXP B (data not shown). Soil water repellency is evident when extreme dry periods occur (Imeson et al., 1992). Perhaps there was no SWR during EXP A because there was enough precipitation (at least 0.69 cm every month) to not have extreme dry periods persist, where the soil moisture content is below $0.05 \text{ cm}^3 \text{ cm}^{-3}$.

Another explanation for no SWR may be because the experimental field was tilled. Blanco-Canqui and Lal (2009) found that no-till farming slightly increased SWR in a regional study across 11 soil series (Gilpin channery silt loam, Crider silt loam, Maury silt loam, Lenawee silty clay loam, Doles silt loam, Chili loam, Canfield silt loam, Ravenna silt loam, Morris channery loam, Holly silt loam, Hagerstown clay loam) in Kentucky, Ohio, and Pennsylvania. A similar finding was found in Scotland where soil under no-till systems was found to be more water repellent than soils under tilled systems (Hallett et al., 2001). In no-till systems, crop residues remain on the surface, ultimately increasing the soil organic matter content. Blanco-Canqui and Lal (2009) suggest that the increase in organic matter in the surface soil can lead to SWR. When a field is tilled, mineralization rates are enhanced, reducing the amount of organic material present to promote SWR (González-Peñaloza et al., 2012). Perhaps the potentially hydrophobic materials were not yet present in the soil for SWR to develop (Hallett, 2008); or that the proportion of soil particles with hydrophobic coatings affects the level of repellency. Such that in the present study SWR was not present due to there being a high enough
proportion of non-hydrophobic tissue components to hydrophobic components within the soil (Doerr et al., 2006). Similar to our results, a long-term farm study in the Netherlands found oat and rye (A. strigosa and S. cereale) CC did not affect SWR (Martínez-García et al., 2018). In the current study, SWR was measured while the CC were growing and five days after termination, not when the residue was actively decomposing.

**Soil Temperature**

For each experiment, measuring event influences the soil temperature (measuring event as random variable resulted in a \( P \leq 0.0001 \) for EXP A and EXP B), thus soil temperature data was analyzed by measuring event (Table 3.3). Mean soil temperatures during EXP A ranged from 10.2°C to 27.0°C with the highest temperatures during the first month of measurements (Table 3.3). Although not significant, the soil temperature was highest under mustard for 75% of all measuring events (Table 3.3). The coldest soil temperatures did not consistently occur under one treatment (Table 3.3).

Mean soil temperatures during EXP B ranged from 9.3 °C to 23.9°C with the highest temperatures during the last month of the experiment (Table 3.4). Soil temperatures were affected by CC treatment on November 29\(^{th}\) and December 13\(^{th}\) (Table 3.4). On November 29\(^{th}\), the fallow/pigweed treatment had the highest soil temperature compared to the CC treatments. On December 13\(^{th}\), the fallow/pigweed treatment had the highest soil temperature which was similar to red clover, radish and mustard. Although
not significant the soil temperature was lowest under the crimson clover treatment 40% of all EXP B measuring events (Table 3.4).

In a long-term study conducted in south-central Kansas, Blanco-Canqui et al. (2011) reported that the summer soil temperature under sunn hemp and under a late-maturing soybean were both consistently lower than under fallow plots. Cover crops are commonly known to moderate soil temperature in temperate soils (Blanco-Canqui et al., 2015). Perhaps, temperatures during which the CC were grown in were not extreme enough to see the consistent effects of CC on soil temperature. Perhaps soil temperatures under plants during winter months are more controlled by solar radiation than temperatures. Fu and Rich (2002) found that average soil temperatures were correlated to incoming solar radiation and elevation in Gunnison County Colorado under a variety of different topographic conditions.

**Biomass**

At the end of EXP A, similar mean fresh biomass was determined among CC treatments and ranged from 16,040 to 53,706 kg ha$^{-1}$ ($P = 0.0828$, Figure 3.2a). Although not significant, the fallow/pigweed treatment had the least fresh biomass. Cover Crop treatment influenced EXP A dry biomass ($P = 0.0141$, Figure 3.2b.) with crimson clover, mustard, and oats being the only CC that had greater dry biomass than the fallow/pigweed treatment (Figure 3.2a).
At the end of EXP B, the mean fresh biomass ranged from 1,905 to 34,664 kg ha$^{-1}$ ($P \leq 0.0001$, Figure 3.2c). Crimson clover had greater fresh biomass than radish, mustard, red clover, and oats (Figure 3.2c). Red clover and oats had less fresh biomass than the fallow/pigweed treatment (Figure 3.2c). Cover crop treatment also influenced the dry biomass during EXP B ($P \leq 0.0001$, Figure 3.2d). Annual rye had a greater dry biomass than all treatments except crimson clover (Figure 3.2c). Red clover had the lowest dry biomass which was less than hairy vetch, crimson clover and annual rye and similar to all other treatments (Figure 3.2d).

Greater CC biomass has been documented to increase weed suppression and nutrient uptake by the CC (MacLaren et al., 2019). This can lead to a decreased need for chemical and cultural weed management. Having a greater dry biomass produces an opportunity to build up soil organic matter (P. Muchaonyerwa et al., 2012). Soil organic matter is rich in nutrients and acts as a nutrient reservoir for crops (Lal, 2020). Other benefits of soil organic matter include increasing available water content (Hudson 1994), increasing aggregation (Jangir et al., 2019) and aggregate stability (Chenu et al., 2000) and reduces compaction (Jangir et al., 2019).

**Establishment and Percent Cover**

During EXP A, all treatments reached establishment (80% coverage). All CC treatments took a similar number of weeks to reach 80% cover ranging from 10 to 12 weeks (data not shown). Although not statistically significant, the pigweed found in the fallow/pigweed plots took the longest to establish (12 weeks) meaning that bare soil was
exposed for a longer period to the elements making the soil more susceptible to potential lost from rainfall erosion (which is significant from a practical standpoint) and increasing soil temperatures from solar radiation. All CC treatments reached establishment before winter.

During EXP B, only five CC treatments (annual rye, crimson clover, fallow/pigweed, mustard, and radish) reached establishment. The dryer weather conditions at the beginning of EXP B potentially was the reason for the observed and measured limited establishment and growth of different treatments. Cover crop treatment influenced percent cover on all measuring events for EXP B (Table 3.5). Fallow/pigweed was the quickest to reach establishment and had the highest percent cover on the first measuring event. By the second measuring event, mustard had a similar percent cover to fallow/pigweed and consistently had the highest percent cover from the end of November (which was similar to annual rye, fallow/pigweed and radish) until the end of December when the mustard began to decline. Radish, mustard, and oats began to winter kill in January. Starting at the end of January, annual rye had the highest percent coverage. Red clover consistently had low coverage compared to other treatments. Hairy vetch was slow to grow, but by the last measuring event, was covering 72% of the plot (Table 3.5).

Having a solid establishment before winter helps to protect the soil from erosion by reducing the impact and force of rain drops and subsequently reducing soil dislodgement (Feng et al., 2016). Similar to biomass, percent coverage is also linked to weed suppression. Liebman and Davis (2000) found a positive correlation between
percent coverage and weed suppression. When CCs are able to produce canopy coverage, weeds are suppressed due to light competition (Liebman and Davis 2000).
Figures and Tables

Table 3.1. Comparison of volumetric water content (VWC) (cm$^3$ cm$^{-3}$) for winter cover crop (CC) treatments grown in the Southern Piedmont (Clemson, South Carolina) during 2021-2022 period (EXP A). *, **, and NS = P < 0.05, P < 0.01, and P > 0.05, respectively. †Means followed by the same letter within a column are statistically similar when compared using a Tukey’s HSD test at a significance level 0.05.

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Table 3.2: Comparison of volumetric water content (VWC) (cm$^3$ cm$^{-3}$) for winter cover crop (CC) treatments grown in the Southern Piedmont (Clemson, South Carolina) during 2022-2023 period (EXP B). *, **, ***, and NS = P < 0.05, P < 0.01, P < 0.001 and P > 0.05, respectively. †Means followed by the same letter within a column are statistically similar when compared using a Tukey’s HSD test at a significance level 0.05.

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Table 3.3. Comparison of mean temperatures (°C) for winter cover crop (CC) treatments grown in the Southern Piedmont (Clemson, South Carolina) during 2021-2022 period (EXP A). NS = P > 0.05.

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Table 3.4: Comparison of mean temperatures (°C) for winter cover crop (CC) treatments grown in the Southern Piedmont (Clemson, South Carolina) during 2022-2023 period (EXP B). **,***, and NS = P < 0.01 and P < 0.001 and P > 0.05, respectively. †Means followed by the same letter within a column are statistically similar when compared using a Tukey’s HSD test at a significance level 0.05.

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Table 3.5: Comparison of mean percent cover (%) for winter cover crop treatments grown in the Southern Piedmont (Clemson, South Carolina) during 2022-2023 period (EXP B). ** and *** = P < 0.01 and P < 0.001, respectively. †Means followed by the same letter within a column are statistically similar when compared using a Tukey’s HSD test at a significance level 0.05.

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<td>7 c</td>
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<tr>
<td>Mustard</td>
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Figure 3.1: Comparison of the weekly mean temperature (°C) and weekly rainfall accumulation (cm) of the 5-year historical average from 2017 to 2021 and (a) the EXP A 2021-2022 period, and (b) the EXP B 2022-2023 period for Clemson South Carolina. Arrows identify the first day of experiments and day of cover crop (CC) termination.
Figure 3.2. Comparison of fresh and dry biomass (kg/ha) ± std error for winter cover crop treatments grown in the Southern Piedmont (Clemson, South Carolina) during 2021-2022 period (a and b) (EXP A) and 2022-2023 period (c and d) (EXP B). † Means followed by the same letter within a graph are statistically similar when compared using a Tukey’s HSD test at a significance level 0.05.
CHAPTER FOUR

CONCLUSIONS

Soil Volumetric Water Content and Soil Temperature

The results of this field study suggest that CC in the southern piedmont region of South Carolina have minimal impact on VWC, soil temperature, and SWR. Volumetric water content and soil temperature seem to be affected more by variability in climate. As documented in the first experiment in which CC established quickly, CC treatment influenced soil VWC following drier periods. In comparison, during the second experiment in which dry weather persisted for the first twelve days, resulted in slow establishment and cover of the plot area. As a drought period persisted, perhaps soil which was most covered (i.e. Mustard in December) would be expected to have the highest VWC, as most of the plant available water has been utilized, leaving the CC treatments with the most cover reducing water loss in the vapor phase, resulting in higher soil VWC underneath them. When there was a CC treatment effect on soil temperature, soils under the fallow/pigweed treatment was the highest.

Soil Water Repellency

Soil water repellency was not present at any measuring events for EXP A and EXP B. The tilled field, no prolonged dry periods persisting, and measurements taken
before CC residues had decomposed may all be attributed to the lack of SWR determined.

**Biomass and Percent Cover**

The results of this field study also show that CC treatments influence biomass and percent coverage. In both experiments, red clover had low fresh and dry biomass, suggesting that it may not be an ideal CC for weed suppression and building organic matter, although it could be grown in fields where a nitrogen credit is desired for the subsequent cash crop. Crimson clover, another nitrogen fixer, had one of the highest biomasses, and thus would be a better selection for weed suppression, building organic matter, and for supplying nitrogen to the subsequent crop. Annual rye and hairy vetch were higher biomass producers for both experiments suggesting more tolerance to rainfall variations. Erosion is the main reason why farmers plant CC in the southern Piedmont region. Erosion is more likely to occur when CC do not establish, and soil is exposed. When there was some rainfall within a day of planting, all CC reached establishment before the winter months (EXP A), and thus there would be less potential for erosion to occur. When there was no rain event before and until 12 days after planting, CC treatments differed in percent coverage (EXP B) and thus there was more potential for soil erosion to occur. This suggests that adequate rainfall at time of planting is crucial for CC growth and performance, and which might subsequently impact erosion potential. Annual rye, which is not as commonly grown as a CC as cereal rye is in the southern Piedmont, had a high biomass regardless of rainfall. The high biomass and presence of
surface roots of annual rye suggest that it is the preferred CC for reducing erosion potential. Investigating performance of other winter CC, and CC grown during summer months may identify better plants for desired field and environmental benefits.
WORKS CITED


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