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Fall–winter cover crops promote soil health and weed control in the southeastern clayey soils

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Abstract

Seven winter cover crops including grasses, legumes, and brassicas were evaluated for biomass production and effects on weed presence, stored soil water, soil health indicators, and the performance of a subsequent soybean [*Glycine max* (L.) Merr.] crop in the clayey soils of South Carolina during 2019–2020 and 2020–2021. A mixture of Austrian winter pea (*Pisum sativum* L.), rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* Roth), and oat (*Avena sativa* L.), a mixture of crimson clover and rye, and single rye ranked high for biomass production. Cover crops did not deplete more soil water than a fallow did (–22 to 8% difference in soil water retention, compared to fallow with or without herbicide application), controlled weeds equally well or better than herbicides (>90% reduction in weed presence, compared to herbicide control), and reduced soil penetration resistance (>40%, compared to fallow with or without herbicide application in the second season). The five-species mixture also improved soil biological activity (>43% increase in soil respiration at cover-crop termination, compared to that under a chemical fallow). The subsequent soybean crop's yield was never negatively affected if not improved by the above cover crops (9–173% increase, compared to that following a chemical fallow). Our results indicate the suitability of the above cover crops for the southeastern clayey soils based on biomass production, weed suppression, and improvements in soil health and the subsequent soybean crop's performance and provide the rationale for planting them rather than keeping the land under a chemical fallow.

1 | INTRODUCTION

The production agriculture in the southeastern United States is facing unique challenges with soils that are highly degraded. Most of these soils have low organic matter content and water holding capacity and poor structure and fertility, impairing crop productivity and agroecosystem sustainability (Swaby et al., 2016). Climatic conditions in this region, including intense and poorly distributed rainfall, are contributing to soil degradation (e.g., weathering, leaching of nutrients, and erosion due to rainfall), while intensive tillage is exacerbating the issue (Novak & Busscher, 2013; Sivakumar & Stefanski, 2007; Thaler et al., 2021). Most southeastern agricultural fields have a subsurface compacted zone (hardpan) limiting root penetration, which predisposes crops to drought stress

Abbreviations: DAP, days after planting; WEOC, water-extractable organic carbon; WEON, water-extractable organic nitrogen.

and reduces yields (Khalilian et al., 2014; Marshall et al., 2016; Raper et al., 2005). A good example is the red clayey soil (Ultisols), which is prevalent in the Southeast. To manage soil compaction, farmers practice deep tillage, which adds to production cost, consumes organic matter, and leaves the soil prone to recompaction. To address these challenges, conservation management practices are essential, which will prevent soil organic C losses while maintaining soil health and productivity.

Interest in cover cropping and conservation tillage is growing among the southeastern row-crop farmers because they address soil compaction and improve soil health, biodiversity in agroecosystems, and resilience to extreme weather. According to the 2017 census of agriculture, more than 5% of the total farmland hectares adopt cover crops in many southeastern states (USDA-NASS, 2017). Furthermore, multispecies cover crops (mixtures) have been increasing in popularity recently (Couëdel et al., 2018; Florence & McGuire, 2020; Nielsen et al., 2015a; R. G. Smith et al., 2014; Wendling et al., 2017). The diversity of the mixture with the involvement of the grass, legume, and brassica functional groups in various combinations often provides enhanced benefits to soil health and weed suppression and promotes higher yields of the subsequent crop as compared with single-species cover crops (Q. A. Khan & McVay, 2019). The different components of cover crop mixtures complement each other through diverse mechanisms such as varied biomass production, residue decomposition rates, rooting patterns, dinitrogen (N_2) fixation, C/N ratios, and production of allelopathic chemicals (Q. A. Khan & McVay, 2019; Magdoff & Van Es., 2009). However, any advantage of multispecies cover crops over single-species cover crops depends upon many factors such as location, species, soil type, and soil nutrient and water conditions (Florence & McGuire, 2020; Nielsen et al., 2015b; Reberg-Horton et al., 2012; Wells et al., 2013).

Though cover crops offer important ecosystem services, to achieve any of those benefits, cover crop selection and management practices need to be optimized and adapted to specific climatic and edaphic conditions (Abdalla et al., 2019; Blanco-Canqui et al., 2015; Shackelford et al., 2019). Knowledge of the suitable cover crops for different localities and cropping systems, seed and planting costs, and potential impacts on plant-available soil moisture and nutrients, and cash crop productivity will support producer adoption of cover crops in the Southeast. A recent survey in South Carolina indicated farmers' desire to get more information regarding effective cover crops for their locality (Clay et al., 2020). Historically, the long-term benefits of cover crops have received attention; however, in recent years, the short-term benefits of cover crops are gaining importance. The present study evaluated the short-term benefits of some commonly available cover crops in the region to generate information that would be beneficial for growers to choose cover crop species. The specific objectives of this study were to evaluate seven winter cover crops (grasses, legumes, and brassicas as single species or mixtures) for biomass production and determine the effects of cover crops on weed presence, stored soil water, soil health, and the performance of the following soybean [*Glycine max* (L.) Merr.] crop. We hypothesized that the high biomass-producing single- and multi-species cover crops will reduce weed presence and improve soil health without depleting more soil water than a fallow does.

Core Ideas

- We found two- and five-species grass-legume mixtures that produced the same amount of biomass as rye.
- The above mixtures and rye did not deplete more soil water than a fallow did.
- All three suppressed weeds, reduced soil penetration resistance, and maintained or improved subsequent soybean yield.
- The five-species mixture also enhanced soil biological activity relative to a fallow.
- Our results demonstrate the advantage of fall-winter cover crops over keeping the land under a chemical fallow.

The cover crops tested in this study as single species or in mixtures included rye (*Secale cereale* L.), oat (*Avena sativa* L.), wheat (*Triticum aestivum* L.), crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* Roth), Austrian winter pea (*Pisum sativum* L.), turnip (*Brassica rapa* subsp. *rapa*), and radish (*Raphanus sativus* L.). A rye cover crop is often grown for its high biomass production and ability to add organic matter, scavenge excess N, prevent erosion, and suppress weeds (Clark, 2012; Vann et al., 2018). Oat and wheat are two other grass cover crops that suppress weeds, prevent erosion, scavenge excess nutrients, and add organic matter (Clark, 2012). Crimson clover is a legume cover crop commonly grown for its ability for N_2 fixation, soil building, and erosion prevention, and as a forage (Clark, 2012; Vann et al., 2018, 2019). Hairy vetch is a legume cover crop grown as a N source, weed suppressor, topsoil conditioner, and erosion reducer (Clark, 2012; Vann et al., 2019). Austrian winter pea is another legume that is grown as a plow-down N source, weed suppressor, and forage (Clark, 2012; Vann et al., 2019, 2021). Brassicas such as radish and turnip produce large taproots that can penetrate deep soil layers ("bio-drilling"), alleviate compaction, scavenge nutrients from deep in the soil profile, and provide macrochannels that facilitate water infiltration (Clark, 2012; Saini et al., 2005). The present study is the first one testing the effectiveness of the above cover crops

TABLE 1 Results of soil tests conducted before cover crop planting in season-1 and season-2

Soil parameter/nutrients	Season-1	Season-2
Soil pH	6.4	6.6
Phosphorus, kg ha^{-1}	77.33 (High)	11.21(Low)
Potassium, kg ha^{-1}	230.9 (Sufficient)	102 (Medium)
Calcium, kg ha^{-1}	1278 (Sufficient)	855 (Medium)
Magnesium, kg ha^{-1}	306 (Sufficient)	238 (Sufficient)
Zinc, kg ha^{-1}	4 (Medium)	2 (Low)
Manganese, kg ha^{-1}	49 (Sufficient)	22 (Medium)
Boron, kg ha^{-1}	0.3 (Medium)	0.6 (Medium)
Copper, kg ha^{-1}	0.9	1.01
Sodium, kg ha^{-1}	9	7
Nitrate N, kg ha^{-1}	36	–[a]
Organic matter, %	3.4	3.4

Note. The remarks, low, medium, sufficient, and high indicate soil nutrient status provided in the soil test results.
[a]Not measured.

as single species or in mixtures based on soil water depletion, weed suppression, and soil health in the clayey soils of South Carolina.

2 | MATERIALS AND METHODS

2.1 | Experiment site and management

The field studies were conducted in 2019–2020 (season-1) and 2020–2021 (season-2) at the Piedmont Research and Education Center at Pendleton (34˚37′30.1″ N, −82˚44′13.9″ W, 253 m asl) in northwestern South Carolina, which is characterized by red clayey soils (Ultisol) (based on the USDA NRCS Soil Survey). The soil series at the study site is Cecil (fine, kaolinitic, thermic typic Kanhapludult) with sandy loam soil in the first 15 cm and red clayey soil from 15 to 100 cm (based on the USDA-NRCS Web Soil Survey). Before the study in 2019, the cropping sequence was a 2-yr soybean–corn (*Zea mays* L.) rotation and the land was left fallow in fall except in 2016 and 2018 when oat replaced the fallow.

In season-1, field preparation included chisel plowing (Model no. 156 D75242, Athens Plow Company) to a depth of 20 cm 4 d before cover crop planting, and harrowing with a field cultivator (Model Perfecta II no. 3265, Unverferth Manufacturing) 1 d before cover crop planting. Tillage operations were not conducted in season-2. To determine the soil nutrient status before cover crop planting, composite soil samples were collected from the study site on 25 Oct. 2019 in season-1 (4 d before cover crop planting) and 19 Nov. 2020 in season-2 (1 d before cover crop planting). The soil samples were analyzed at the Clemson University Agricultural Service Laboratory, Clemson, SC. According to the soil test results (Table 1), the research site did not have nutrient deficiencies in season-1 but had P and Zn deficiencies in season-2. However, P and Zn were not supplemented in season-2 since we did not want to apply any fertilizers to support cover crop growth as farmers in our region usually do.

2.2 | Cover crop management

The seven cover crop treatments that were used in the present study and the functional groups involved in the two-species mixtures and five-species mixtures are given in Table 2. The mixture of five-a is a five-species mixture marketed by the popular seed vendor in the southeastern United States, Adams-Briscoe Seed Company. The mixture of five-b is recommended as a “soil health building cover crop mix” by the USDA-NRCS (USDA-NRCS, 2015).

Cover crops were planted using a four-row cone planter (Allan Machine Company) on 29 Oct. 2019 in season-1 and on 20 Nov. 2020 in season-2. Row spacing was 0.17 m in both seasons. The seeding rate of single species cover crops followed the values provided by Clark (2012) (Table 2). The seeding rate of individual species in the mixtures was determined by dividing the seeding rate of the species when used as a monoculture by the number of species in the mixture (Wortman et al., 2012). The control treatments were fallow with herbicide application (chemical fallow; control-1) and fallow without herbicide application (control-2). Weeds were controlled in control-1 plots using the broad-spectrum herbicide Roundup [glyphosate, N-(phosphonomethyl)glycine] (Monsanto) at the rate of 0.82 kg acid equivalent (a.e.) ha^{-1} at 93 d after cover crop planting (DAP) in season-1 and at 96 and 151 DAP in season-2.

Each “cover-crop” or “control” plot was 6.1 by 6.1 m in size and a 2-m alley separated the individual plots. The plots were

TABLE 2 Cover crop treatments and crops that were components of each treatment, their functional groups, seeding rate, and fractional compositions

Treatment	Crop	Species	Seeding rate	Fractional composition[a]	Functional group
			kg ha^{-1}	%	
	Single species				
Single species-a[b]	Rye	*Secale cereale* L. cultivar Wrens Abruzzi	112.1	100	Grass
Single species-b[b]	Crimson clover	*Trifolium incarnatum* L. cultivar Dixie	33.6	100	Legume
	Mixture of two species				
Mixture of two-a	Rye	*Secale cereale* L. cultivar Wrens Abruzzi	56	75	Grass
Mixture of two-b	Crimson clover	*Trifolium incarnatum* L. cultivar Dixie	16.8	25	Legume
	Crimson clover	*Trifolium incarnatum* L. cultivar Dixie	16.8	56	Legume
	Turnip	*Brassica rapa* subsp. *rapa*. cultivar Purple top white globe	5.6	44	Brassica
Mixture of two-c[b]	Oat	*Avena sativa* L. cultivar Coker 227	56	34	Grass
	Radish (Daikon)	*Raphanus sativus* var. Longipinnatus	11.2	66	Brassica
	Mixture of five species				
Mixture of five-a	Austrian winter pea	*Pisum sativum* L. *ssp. sativum* var. arvense	26.9	13	Legume
	Rye	*Secale cereale* L. cultivar Wrens Abruzzi	22.4	50	Grass
	Crimson clover	*Trifolium incarnatum* L. cultivar Dixie	6.7	12	Legume
	Hairy vetch	*Vicia villosa* Roth cultivar Namoi	8.9	13	Legume
	Oat	*Avena sativa* L. cultivar Coker 227	22.4	12	Grass
Mixture of five-b	Oat	*Avena sativa* L. cultivar Coker 227	22.4	16	Grass
	Wheat	*Triticum aestivum* L. cultivar Georgia. gore	22.4	33	Grass
	Crimson clover	*Trifolium incarnatum* L. cultivar Dixie	6.7	20	Legume
	Radish (Daikon)	*Raphanus sativus* var. Longipinnatus	4.5	25	Brassica
	Turnip	*Brassica rapa* subsp. *rapa*. cultivar Purple top white globe	2.24	6	Brassica

[a]Fractional composition of a component in a mixture = (seeding rate of that component in the mixture/sum of seeding rates of all components in the mixture) × 100 (Causarano et al., 2006; Franzluebbers, 2005; Reberg-Horton et al., 2012).
[b]The letters "a", "b", and "c"" are used to denote different mixtures.

arranged in a randomized complete block experimental design (RCBD) with five blocks (replications). The seven cover crop treatments and two fallow treatments were randomly assigned to plots within each of the five blocks. Plots received the same cover crop treatments in both seasons. The trials were not irrigated in both seasons. Cover crops were terminated by mowing using a dirt dog mower (Model no. RC106, Dirt Dog Manufacturing) on 22 Apr. 2020 in season-1 and on 28 Apr. 2021 in season-2. The residues were accidentally baled in season-1 but left on the surface in season-2.

2.3 | Soybean management

Soybean cultivar, Musen (developed and released by Clemson University, SC) (maturity group VI) was sown at 50 kg ha^{-1} with a row spacing of 38 cm on 11 June 2020 in season-1 (50 d after cover crop termination) and on 25 June 2021 in season-2 (58 d after cover crop termination) using a no-till John Deere planter (Model no. 1590, Deere & Company). In season-1, herbicides, Glufosinate-ammonium [D,L-phosphinothricin or 2-amino-4-(hydroxymethylphosphinyl)butanoic acid] (BASF Corporation) at the rate of 0.64 kg a.i. ha^{-1}, Envive {Chloroimuron ethyl, Ethyl 2-[[[[(4-chloro-6-methoxy pyrimidin-2-yl)amino]carbonyl]amino]sulfonyl]benzoate, Flumioxazin, 2-[7-fluor-3,4-dihydro-3oxo-4-(2-propynyl)−2H-1,4-benzoxazin-6-yl]−4,5,6,7-tetrahydro1H-isoindole-1,3(2H)-dione and Thifensulfuron methyl, Methyl 3-[[[[(4-methoxy-6-methyl-1,3,5- triazin-2-yl)amino]carbonyl] amino] sulfonyl]−2-thiophenecarboxylate} (Dupont) at the rate of 0.12 kg a.i. ha^{-1}, and Prowl H2O [pendimethalin: N-(1-ethylpropyl)−3,4-dimethyl-2,6-dinitrobenzenamine] (BASF Corporation) at the rate of 1.06 kg a.i. ha^{-1} were applied on the same day of soybean planting. The soybean crop was maintained under rainfed conditions without any irrigation in both seasons.

2.4 | Environmental conditions during the cover crop and soybean seasons

Figure 1 shows the precipitation and air temperature data from the planting of cover crops through the harvest of the following soybean crop in comparison with the climate normal. Total precipitation was 183 cm during the 385-d period in season-1 and 146 cm during the 364-d period in season-2. Season-1 was wetter than normal based on the 30-yr historic precipitation data. Season-2 was drier than normal during the cover crop season, but it received normal precipitation amounts during the soybean season.

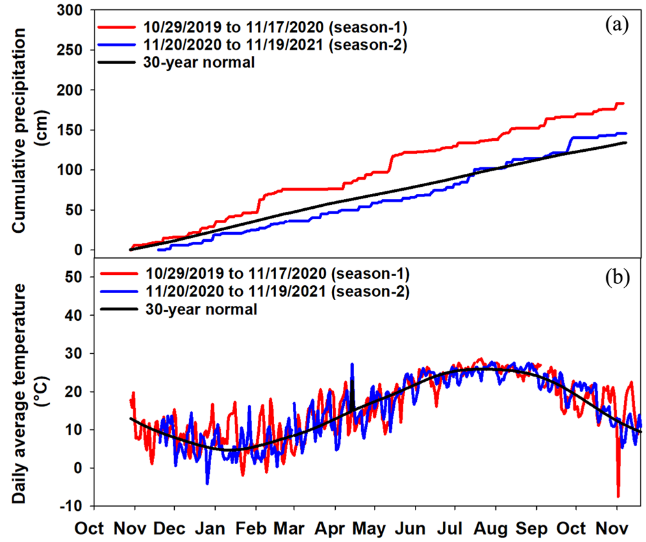

FIGURE 1 (a) Cumulative precipitation and (b) daily average temperatures from the planting of cover crops through the harvest of soybean in comparison with the 30-yr normal data. Cumulative precipitation normals for a period of 388 d in both seasons were calculated from the daily precipitation normal for a period of 30 yr from 1991 to 2020. Precipitation and temperature data were obtained from the National Centers for Environmental Information, a division of the National Oceanic and Atmospheric Administration

2.5 | Data collection

2.5.1 | Cover crop biomass

In season-1, aboveground cover crop biomass was measured at 115 (all cover crops at the vegetative stage), 144 (radish, rye, and turnip at the flowering stage, other cover crops at the vegetative stage), and 170 (all cover crops except Austrian winter pea at the flowering stage) days after planting. In season-2, it was measured at 111 (all cover crops at the vegetative stage), 143 (radish, rye, and turnip at the flowering stage, other cover crops at the vegetative stage), and 159 (all cover crops at the flowering stage) DAP. On the first two measurement dates (115 and 144 DAP in season-1 and 111 and 143 DAP in season-2), biomass was manually harvested from a randomly chosen 0.5-m^2 area in each plot. To avoid any edge effects, 1 m from the edge was avoided on each side of the plots, when harvesting biomass. The final biomass measurement (at 170 DAP in season-1 and 159 DAP in season-2) was conducted right before cover crop termination in both seasons, and biomass was harvested from a 7.4-m^2 area (1.22 by 6.10 m) in each plot using a forage harvester (Carter manufacturing Co., Inc). Biomass samples were dried at 55 ˚C to constant weight for determining the dry weight (Dabney et al., 2001).

2.5.2 | Weed presence

Weed presence was determined during the cover crop growing season at 93 and 125 DAP (cover crops were at the vegetative stage on both measurement days) in season-1 and at 95 (all cover crops at the vegetative stage) and 130 DAP (radish at the flowering stage, other cover crops at the vegetative stage) in season-2. Weed presence was measured by a "point intercept method" (Elzinga et al., 2001), for which a quadrat with an internal dimension of 60 × 60 cm (L × W) was randomly placed in each plot. The quadrat had 11 straight chains, which were 5-cm spaced apart, along the length and width resulting in 121 transects (points). The number of transects hitting weed plants was counted in each plot. Weed presence in each plot was estimated as the ratio between the number of "hits" on the weed species to the total number of transects in the quadrat, and was expressed as a percentage (Bonham, 2013; Elzinga et al., 2001; Rowe, 2015).

2.5.3 | Volumetric soil water content

Volumetric soil water content was measured at 111 (all cover crops at the vegetative stage), 143 (radish, rye, and turnip at the flowering stage, other cover crops at the vegetative stage), and 165 (all cover crops except Austrian winter pea at the flowering stage) DAP in season-1 and at 112 (all cover crops at the vegetative stage), 143 (radish, rye, and turnip at the flowering stage, other cover crops at the vegetative stage) and 154 (all cover crops at the flowering stage) DAP in season-2 during the cover crop growth season. Measurements were also taken during the soybean growing period at 7 and 53 d after soybean planting in season-1 (i.e., 57 and 103 d, respectively, after cover crop termination) and 88 d after soybean planting in season-2 (i.e., 146 d after cover crop termination). A PR2 capacitance probe (PR2/6, Delta-T Devices Ltd.) was used to measure volumetric soil water content. Measurements were taken at 10-, 20-, 30-, 40-, and 60-cm depths following the manufacturer's protocol (Delta-T Devices, 2019). To measure volumetric water content with the PR2 probe, a 1-m long access tube was installed at the center of each plot. The total stored soil water (m) to a depth of 60 cm was estimated using volumetric soil water content values at 10-, 20-, 30-, 40-, and 60-cm depths and the respective depth intervals (0.1, 0.1, 0.1, 0.1, and 0.2 m) as followed: total stored soil water (m) to a depth of 60 cm = 0.1 (sum of individual volumetric soil water contents at 10-, 20-, 30-, and 40-cm depths) + 0.2 (volumetric soil water content at 60-cm depth) (Narayanan et al., 2013).

2.5.4 | Soil health

Soil penetration resistance

Soil penetration resistance was measured using the Soil Compaction Tester (Dickey-John Corporation), which is a hand-held cone penetrometer. The Soil Compaction Tester shaft was pushed down to the soil in each plot with constant force and the soil depth at which the penetration resistance reached 2.07 MPa (300 PSI which can stop the root growth of crop plants [Taylor & Gardner, 1963]) was recorded. The measurements were taken at two random spots in each plot to get an average depth value per plot. In season-1, measurements were taken at 5 d before cover crop termination and 152 d after cover crop termination (i.e., 102 d after soybean planting). In season-2, measurements were taken at 40 d after cover crop termination and 96 d after cover crop termination (i.e., 38 d after soybean planting).

Soil respiration and water extractable soil carbon and nitrogen

To measure soil respiration, water-extractable soil organic carbon (WEOC), and water-extractable soil organic nitrogen (WEON) at the end of the cover crop growing period, soil samples were collected using a 2.5-cm diam. sampling core using a gas-powered core sampler (AMS Inc). Soil samples were collected to a depth of 15 cm (as per the soil-testing laboratory's protocol) where a large proportion of the active root zone is. Soil samples were collected 7 d before cover crop termination in season-1 and 9 d after cover crop termination in season-2. Four samples were collected from random locations in each plot and homogenized in a bucket to obtain composite samples, which were transferred to labeled Ziploc plastic bags (Reynolds Consumer Products, Inc.). Samples were transported to the laboratory in a cooler. Afterward, soil samples were sent to the Ward Laboratories, Inc, for the Haney Soil Health Test, which quantifies soil health based primarily on soil biology. It measures soil respiration as the amount of CO_2–C a soil can produce over a 24-h incubation period following a significant drying and rewetting event using a Solvita gel system (Woods Ends Laboratory). The WEOC and WEON represent the pool of organic C and N, respectively, that are readily available to the microbes (Haney et al., 2012).

2.5.5 | Soybean performance

Soybean plant height was measured as the distance between the ground level and the top extremity of the plant using a ruler (Lee et al., 1996). Measurements were made at 97 d after soybean planting in season-1 and 96 d after soybean planting in season-2. In both seasons, height was measured for two randomly chosen plants in each plot and averaged to get a single value per plot.

To measure soybean biomass, the total aboveground biomass was hand-harvested from 1-m row length of the seventh row in each plot (there were a total of 16 rows in each plot). When harvesting biomass, at least 1 m was avoided from the ends of the row to avoid any edge effect. Biomass was harvested at 36 d after soybean planting in season-1 and 33 d after soybean planting in season-2. Biomass samples were dried to constant weight at 70 ˚C to determine the dry weight (Fried et al., 2019; Wahbi et al., 2018). Biomass was calculated on a land-area basis (kg ha^{-1}) in each plot by dividing the biomass dry weight from 1 m of harvested row length in that plot by the harvested area. The harvested area was calculated by multiplying the harvested row length by row spacing.

At full maturity growth stage R8 (Fehr et al., 1977), plants were harvested for measuring seed yield. In season-1, plants from a 7.4-m^2 area in each plot were harvested using a Kincaid T19 combine harvester (Kincaid) to measure seed yield. In season-2, plants within a randomly placed 0.5-m^2 quadrat in each plot were hand-harvested to measure seed yield.

2.6 | Data analysis

Analysis of variance (ANOVA) for all data was performed with the GLIMMIX procedure in SAS (version 9.4, SAS Institute). The statistical model for the ANOVA based on a randomized complete block experimental design included the fixed effect of treatment (seven cover crops and two controls). Replication (or block) was considered as a random effect in the analysis. Separation of least squares means was performed using the Fisher's LSD test (α = .05) using the LSMEANS option in the GLIMMIX procedure.

Normality and homogeneity of variance assumptions required for ANOVA were checked for all traits by examining the model residuals. Normality was evaluated with the Shapiro–Wilk test and homogeneity of variance was evaluated with the Levene's test. Evidence of the normality assumption being violated was found for cover crop biomass for some measurement dates, and also for volumetric water content. The lognormal distribution in GLIMMIX was used to redo the ANOVA and LSD for biomass, and the exponential and gamma distributions in GLIMMIX were used to redo the ANOVA and LSD for volumetric water content. The lognormal results for biomass, and the exponential and gamma results for water content, were consistent with the original normal distribution results; suggesting that the normality assumption violation was not significantly impacting the original ANOVA and LSD results. Therefore, tables and figures are based on original scale data for ease of interpretation.

3 | RESULTS

3.1 | Cover crop biomass production

Biomass production of different cover crops ranged between 2,776 and 6,254 kg ha^{-1} in season-1 and between 2,826 and 5,481 kg ha^{-1} in season-2. Overall, the mixture of five-a, rye, and the mixture of rye and crimson clover produced the greatest amounts of biomass and crimson clover, the mixture of crimson clover and turnip, the mixture of five-b, and the mixture of oat and radish produced the least or intermediate amounts of biomass on all measurement dates in both seasons (Figure 2). The cover crops that produced the greatest amounts of biomass were either the single species of rye or the mixtures containing rye (the mixture of five-a and the mixture of rye and crimson clover).

Biomass of individual species in the cover crop mixtures was measured at 144 DAP in season-1. The contribution of the individual species to the total biomass of the mixtures (ratio between the biomass of the species and the total biomass of the mixture, expressed as a percentage) was as followed: rye–75% and crimson clover–25% in the mixture of two-a; crimson clover–56% and turnip–44% in the mixture of two-b; oat–34% and radish–66% in the mixture of two-c; Austrian winter pea–13%, rye–50%, crimson clover–12%, hairy vetch–13%, and oat–12% in the mixture of five-a; and oat–16%, wheat–33%; crimson clover–20%, radish–25%, and turnip–6% in the mixture of five-b. The composition of the mixtures based on the biomass production of individual species (above data) followed the same trend as that of the mixture composition based on the seeding rates of individual species (presented in Table 2).

3.2 | Weed presence during the cover crop growing season

Cover crop treatment had a significant effect on weed presence in both seasons (Table 3). Weed presence under all cover crop treatments was significantly lower than that under a fallow with no herbicide application (control-2) in both seasons (Figure 3a–d). Though control-1 represented a fallow with herbicide application, no herbicides were applied until 93 DAP in season-1 and 95 DAP in season-2. Consequently, weed suppression under all cover crop treatments was greater than that under the control-1 treatment at 93 DAP in season-1 and at 95 DAP in season-2 (Figure 3a and 3c). Even when weeds were managed through herbicide application under control-1 treatment, weed presence in plots with rye, the mixtures of five-a&b, the mixture of rye and crimson clover, and the mixture of oat and radish (high or intermediate amounts of biomass) was similar to or lower than that under the control-1 treatment (Figure 3b and 3d).

3.3 | Volumetric soil water content

In both seasons, the treatment × depth interaction effect was not significant on volumetric soil water content on any measurement dates (Table 3). The total stored soil water content

TABLE 3 Analysis of variance results on the effects of treatments (seven cover crops and two types of fallow controls), depths, and treatment × depth interaction on various traits measured in the study

	Season-1				Season-2			
		P values				*P* values		
Trait	DAP	Treatment	Depth	Treatment × Depth	DAP	Treatment	Depth	Treatment × Depth
Cover crop biomass Production	115	.0008	na	na	111	<.0001	na	na
	144	.0007	na	na	143	<.0001	na	na
	170	.0001	na	na	159	<.0001	na	na
Weed presence during the cover crop season	93	<.0001	na	na	95	<.0001	na	na
	125	<.0001	na	na	130	<.0001	na	na
Volumetric soil water content	111	.3667	<.0001	.9999	112	.0549	<.0001	.9988
	143	.3117	<.0001	.9958	143	.1012	<.0001	.9992
	165	.0055	<.0001	.979	154	.0145	<.0001	.9928
	233	.0065	<.0001	.9424	305	.0351	<.0001	.9876
	279	.0019	<.0001	.9783	na	na	na	na
Total stored soil water in 60 cm depth	111	.8810	na	na	112	.9695	na	na
	143	.8802	na	na	143	.9285	na	na
	165	.1090	na	na	154	.9106	na	na
	233	.4773	na	na	305	.4858	na	na
	279	.3116	na	na	na	na	na	na
Soil depth at which penetration resistance reached 2.07 MPa	171	.7149	na	na	199	.0168	na	na
	328	.8084	na	na	255	.0927	na	na
Soil respiration	169	.0217	na	na	168	.2726	na	na
Water extractable soil carbon	169	.8487	na	na	168	.1335	na	na
Water extractable soil nitrogen	169	.7568	na	na	168	.6077	na	na
Soybean plant height	323	.0002	na	na	313	.0067	na	na
Soybean biomass production	262	.0008	na	na	250	.0944	na	na
Soybean seed yield	385	.0738	na	na	364	.1659	na	na

[a]na, not applicable.

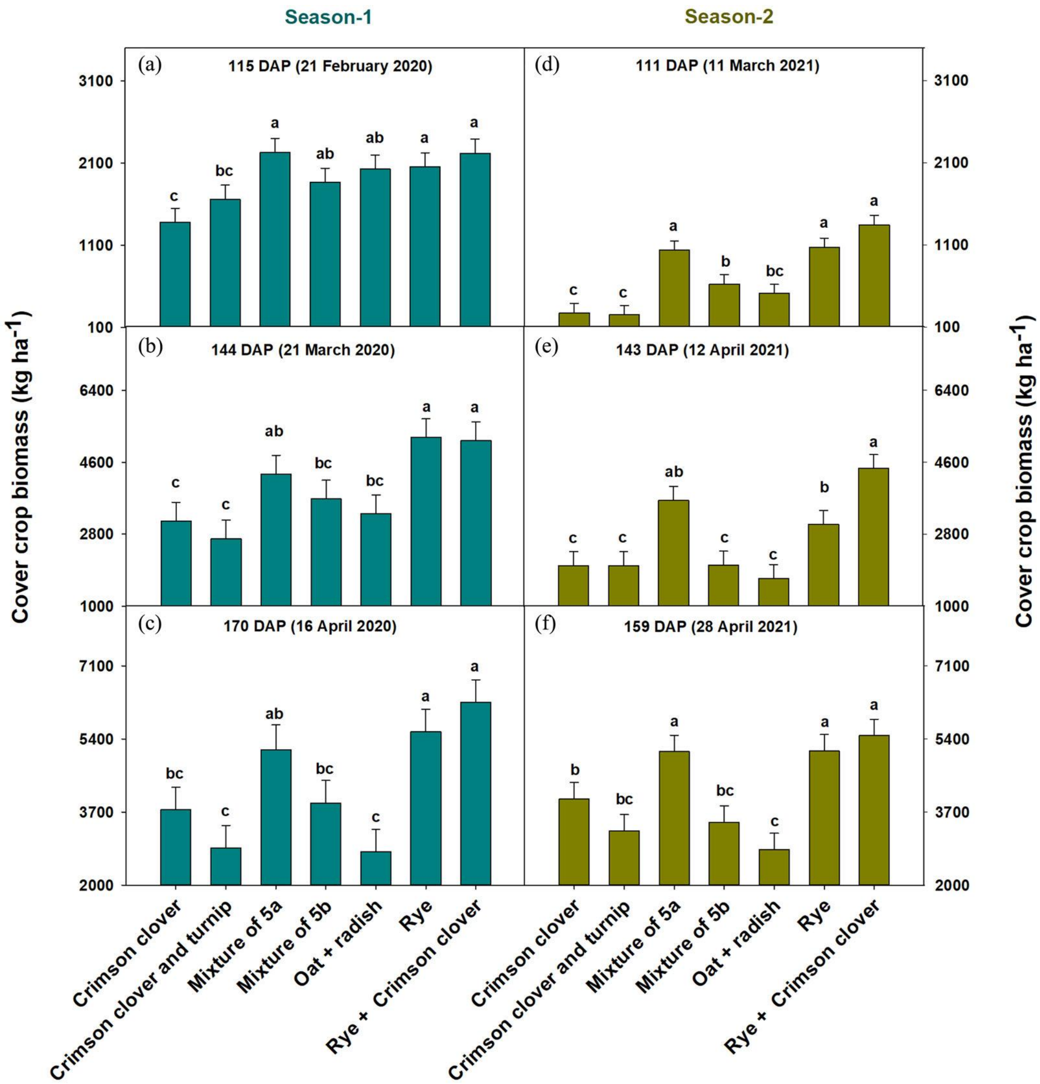

FIGURE 2 (a–c) Cover crop biomass production on various measurement dates in season-1 and (d–f) season-2. Bars (least squares means) with different letters are significantly different according to the LSD test at α = .05. Mixture of 5-a was a combination of Austrian winter pea, rye, crimson clover, hairy vetch, and oat. Mixture of 5-b was a combination of oat, wheat, crimson clover, radish, and turnip. All cover crops were planted on 29 Oct. 2019 in season-1 and 20 Nov. 2020 in season-2. Cover crops were terminated on 22 Apr. 2020 in season-1 and 28 Apr. 2021 in season-2. All cover crops were at the vegetative stage on the first biomass measurement date in both seasons (a and d). By the second biomass measurement date (b and e), radish reached the flowering stage in season-1, and radish, rye, and turnip reached the flowering stage in season-2. By the third biomass measurement date, which occurred at cover crop termination (c and f), all cover crops reached the flowering stage in both seasons, except that Austrian winter pea remained in the vegetative stage in season-1. DAP, days after cover crop planting

to a depth of 60 cm was similar under cover crop treatments and fallow treatments in both seasons, except at 165 DAP in season-1 (Even at 165 DAP in season-1, the total stored soil water in 60 cm depth was lower than that under the fallow treatments for only two cover crops: crimson clover and the mixture of rye and crimson clover) (Table 4). The same result was found after cover crop termination at 233 DAP in season-1 (57 d after cover crop termination, i.e., 7 d after soybean planting), 279 DAP in season-1 (103 d after cover crop termination, i.e., 53 d after soybean planting), and 305 DAP in season-2 (146 d after cover crop termination, i.e., 88 d after soybean planting) (Table 4). Additionally, the total stored soil water to a depth of 60-cm depth did not generally differ among the seven different cover crops (Table 4).

3.4 | Soil health

We measured the effect of cover crops on soil penetration resistance by measuring the soil depth at which the cone penetrometer values reached 2.07 MPa which can stop the root growth of crop plants (Taylor & Gardner, 1963). In season-1, cover crop treatments had no significant effect on the depth to 2.07 MPa, indicating that they had no effect on soil

TABLE 4 Total stored soil water in 60-cm depth during the cover crop season and after cover crop termination. Control-1 represents fallow with herbicide application and control-2 represents fallow without herbicide application. Values in cells represent least squares means ± standard error. Least squares means with different letters are significantly different according to the least significant difference (LSD) test at α = .05. Mixture of 5-a was a combination of Austrian winter pea, rye, crimson clover, hairy vetch, and oat. Mixture of 5-b was a combination of oat, wheat, crimson clover, radish, and turnip

	Stored soil water								
	During the cover crop season						After the cover crop termination		
	Season-1			Season-2			Season-1		Season-2
Treatment	111 DAP[a] (17 Feb. 2020)	143 DAP (20 Mar. 2020)	165 DAP (11 Apr. 2020)	112 DAP (12 Mar. 2021)	143 DAP (12 Feb. 2021)	154 DAP (23 Apr. 2021)	233 DAP[b] (18 June 2020)	279 DAP[b] (3 Aug. 2020)	305 DAP[b] (21 Sept. 2021)
	m								
Control-1	0.191 ± 0.012a	0.191 ± 0.013a	0.177 ± 0.012a	0.254 ± 0.010a	0.250 ± 0.010a	0.224 ± 0.008a	0.148 ± 0.021a	0.156 ± 0.010a	0.183 ± 0.009a
Control-2	0.187 ± 0.012a	0.182 ± 0.011a	0.179 ± 0.0143	0.256 ± 0.010a	0.244 ± 0.010a	0.216 ± 0.008a	0.164 ± 0.012a	0.171 ± 0.013a	0.182 ± 0.009a
Crimson clover	0.180 ± 0.012a	0.177 ± 0.011a	0.139 ± 0.011bc	0.249 ± 0.010a	0.243 ± 0.010a	0.209 ± 0.008a	0.156 ± 0.012a	0.145 ± 0.011a	0.184 ± 0.009a
Crimson clover + turnip	0.198 ± 0.012a	0.192 ± 0.011a	0.159 ± 0.010abc	0.266 ± 0.010a	0.261 ± 0.010a	0.226 ± 0.008a	0.178 ± 0.011a	0.167 ± 0.010a	0.188 ± 0.009a
Mixture of 5a	0.195 ± 0.012a	0.192 ± 0.011a	0.159 ± 0.010abc	0.260 ± 0.010a	0.252 ± 0.010a	0.216 ± 0.008a	0.183 ± 0.011a	0.169 ± 0.010a	0.189 ± 0.009a
Mixture of 5b	0.190 ± 0.012a	0.191 ± 0.011a	0.158 ± 0.011abc	0.259 ± 0.010a	0.253 ± 0.010a	0.221 ± 0.008a	0.174 ± 0.011a	0.161 ± 0.010a	0.181 ± 0.009a
Oat + radish	0.196 ± 0.012a	0.193 ± 0.011a	0.165 ± 0.010ab	0.256 ± 0.010a	0.250 ± 0.010a	0.216 ± 0.008a	0.177 ± 0.011a	0.162 ± 0.010a	0.176 ± 0.009a
Rye	0.202 ± 0.012a	0.194 ± 0.011a	0.157 ± 0.012abc	0.256 ± 0.010a	0.250 ± 0.010a	0.217 ± 0.008a	0.171 ± 0.011a	0.150 ± 0.010a	0.170 ± 0.009a
Rye + crimson clover	0.187 ± 0.012a	0.182 ± 0.011a	0.139 ± 0.011c	0.253 ± 0.010a	0.245 ± 0.010a	0.214 ± 0.008a	0.166 ± 0.011a	0.143 ± 0.010a	0.169 ± 0.009a

[a]DAP, days after cover crop planting.
[b]233 and 279 DAP in season-1 represent 57 and 103 d, respectively, after cover crop termination; 305 DAP in season-2 represents 146 d after cover crop termination.

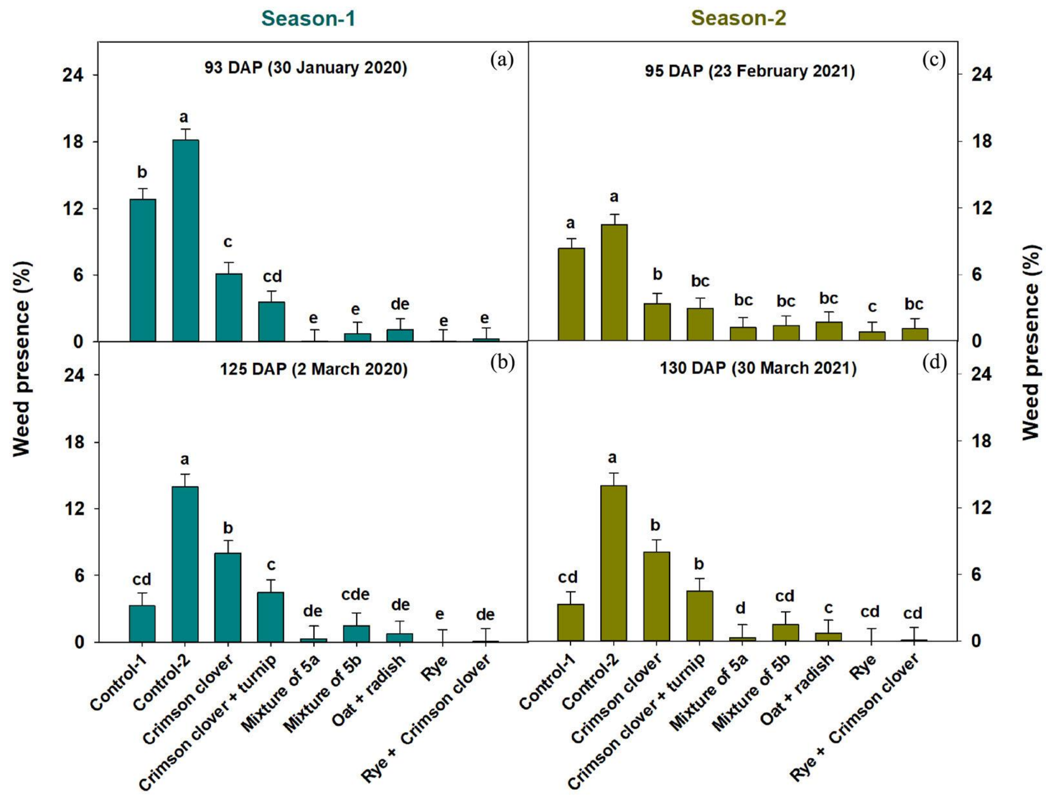

FIGURE 3 (a,b) Effect of cover crop treatments on weed presence in season-1 and (c,d) season-2. Bars (least squares means) with different letters are significantly different according to the LSD test at α = .05. Mixture of 5-a was a combination of Austrian winter pea, rye, crimson clover, hairy vetch, and oat. Mixture of 5-b was a combination of oat, wheat, crimson clover, radish, and turnip. Control-1 was a fallow with herbicide application and control-2 was a fallow without herbicide application. Herbicides were applied in control-1 plots at 93 DAP in season-1 and at 96 and 151 DAP in season-2. DAP, days after cover crop planting

penetration resistance (Table 3). Interestingly, the cover crop effect on soil penetration resistance was significant in the second season. At 40 d after cover crop termination in season-2, soil penetration resistance reached 2.07 MPa only at lower depths on land which was under a rye cover crop, compared to that under fallow treatments with or without herbicide application (control-1&2) (Figure 4c). On the same measurement date, the same trend was observed for the mixture of rye and crimson clover, the mixture of turnip and crimson clover, the mixture of five-a, and the mixture of five-b, when compared to fallow with herbicide application (Figure 4c). At 96 d after cover crop termination in season-2 (i.e., 38 d after planting the soybean crop), again the same trend was observed for rye and the mixture of rye and crimson clover, compared to the fallow treatments with or without herbicide application (control-1&2) (Figure 4d). These results indicate the positive effect of cover crops on reducing penetration resistance.

At cover crop termination, soil respiration values were greater in plots cover cropped with the mixture of five-a, compared to that in plots left as a fallow with herbicide control, in both seasons (Figure 5). At the same time, soil respiration values were not greater in plots cover cropped with rye and the mixture of rye and crimson clover (two other cover crops with high biomass production), compared to that in plots left as a fallow, in both seasons. In season-1, cover crops had no effect on WEOC and WEON (Figure 5). On the other hand, in season-2, WEOC was greater in plots cover cropped with the mixture of five-a and the mixture of rye and crimson clover, compared to that in plots left as a fallow with herbicide control. Similar advantage was not observed for WEON in season-2. However, soil respiration, WEOC, and WEON values were higher in season-2 than in season-1.

3.5 | Soybean performance

We measured the effect of cover cropping on soybean performance by measuring plant height, biomass, and seed yield of soybean grown in plots that were previously under one of the seven cover crop treatments or two fallow treatments. Overall, plant height, biomass, and seed yield of soybean when grown after cover crops were equal to or greater than those of soybean when grown after a fallow with or without herbicide application (Figure 6), indicating that soybean performance was never negatively affected by cover cropping. Furthermore, plant height, biomass, and seed yield of soybean when

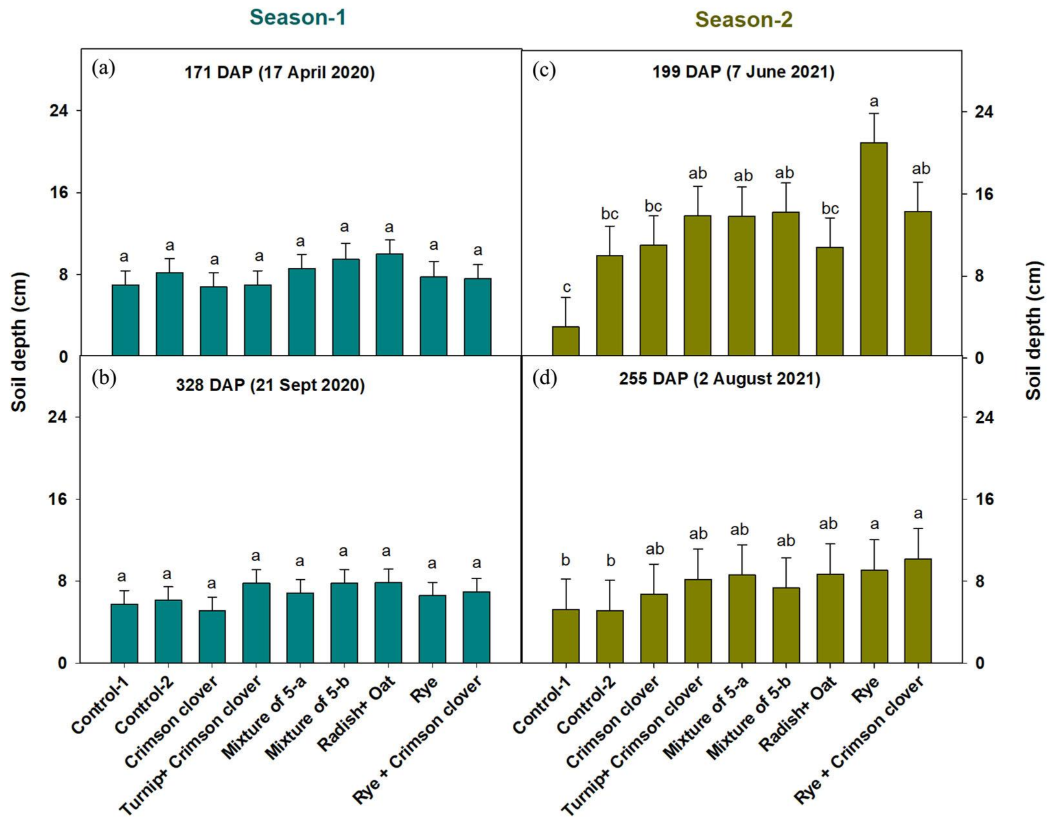

FIGURE 4 (a,b) Soil depth at which penetration resistance reached 2.07 MPa in season-1 and (c,d) season-2 under different cover crop treatments. In season-1, (a) 171 DAP represented 5 d before cover crop termination and (b) 328 DAP represented 152 d after cover crop termination (i.e., 102 d after planting the soybean crop). In season-2, (c) 199 DAP represented 40 d after cover crop termination and 255 DAP represented 96 d after cover crop termination (i.e., 38 d after planting the soybean crop). Bars (least squares means) with different letters are significantly different according to the LSD test at $\alpha = .05$. Mixture of 5-a was a combination of Austrian winter pea, rye, crimson clover, hairy vetch, and oat. Mixture of 5-b was a combination of oat, wheat, crimson clover, radish, and turnip. Control-1 was a fallow with herbicide application and control-2 was a fallow without herbicide application. DAP, days after cover crop planting

grown after a rye cover crop were greater than those of soybean when grown after a fallow with herbicide application (control-1). Additionally, plant height and biomass of soybean when grown after the mixture of five-a were greater than those of soybean when grown after a fallow with herbicide application (control-1).

4 | DISCUSSION

Biomass production is the key to achieving most short-term benefits of cover crops (Mirsky et al., 2013; Teasdale & Mohler, 2000; Van et al., 2018). In the present study, the biomass production of rye (>5,124 kg ha^{-1}), the mixture of rye and crimson clover (>5,480 kg ha^{-1}), and the mixture of five-a (>5,108 kg ha^{-1}) (top three biomass producers in this study) fall in the range of high biomass production of grass and legume cover crops in the Carolina region (Vann et al., 2018, 2019, 2020). Rye is a commonly used cover crop to suppress weeds and for other short-term benefits primarily due to its high biomass production (Reberg-Horton et al., 2012; A. N. Smith et al., 2011). In the present study, the top biomass producers were single species of rye and a two-species mixture and a five-species mixture containing rye. In both mixtures, rye dominated as it produced about 75% of the total biomass in the mixture of rye and crimson clover and about 50% of the total biomass in the mixture of five-a. Thus, the high biomass production of those mixtures was largely contributed by rye.

On the first measurement date (115 DAP in season-1 and 111 DAP in season-2), the biomass values of all cover crops were larger in season-1 than in season-2 (Figure 2a, d). This may be primarily because of residual nutrients from the previous corn season. The biomass values were comparable between seasons for all cover crops on the second and third measurement dates (Figure 2). Any slight decrease in biomass values in the second season might be due to the drier conditions in season-2, compared to season-1.

The biomass production of rye alone, the mixtures of rye and crimson clover, five-a, five-b, and oat and radish that suppressed weed infestation equally well as with herbicide control, during the cover crop season (Figure 3b, d) is practically relevant and should be explored further. Previous

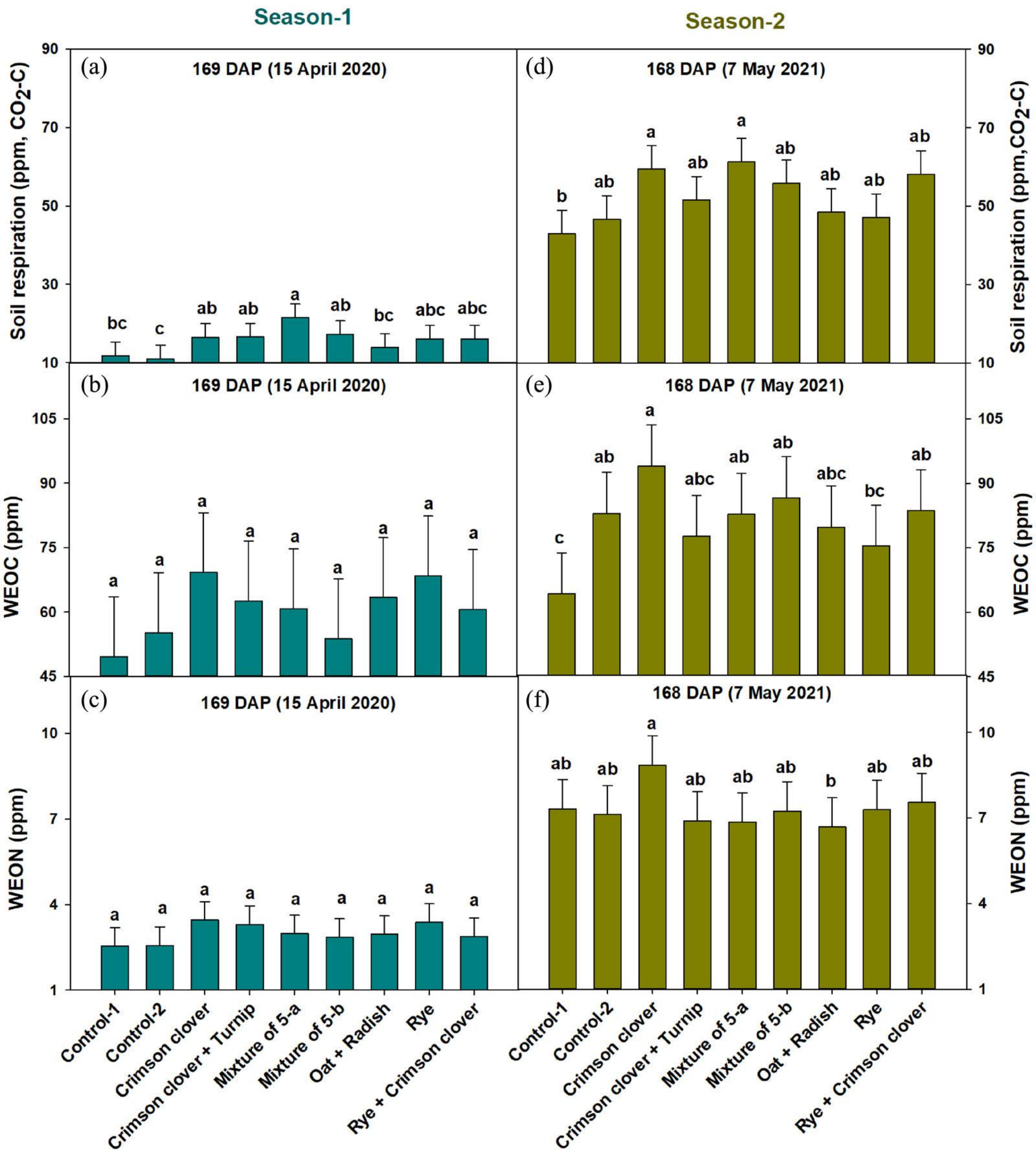

FIGURE 5 Effect of cover crop treatments on soil respiration, water extractable organic carbon (WEOC), and water extractable organic nitrogen (WEON) measured at cover crop termination in season-1 and season-2. Cover crops were terminated on 22 Apr. 2020 in season-1 and 28 Apr. 2021 in season-2. Soil respiration refers to the amount of CO_2–C a soil can produce over a 24-h incubation period following a significant drying and rewetting event, such that the higher the values, the higher the microbial biomass. The WEOC and WEON represent the pool of organic carbon and nitrogen, respectively, that are readily available to the microbes. Bars (least squares means) with different letters are significantly different according to the LSD test at $\alpha = .05$. Mixture of 5-a was a combination of Austrian winter pea, rye, crimson clover, hairy vetch, and oat. Mixture of 5-b was a combination of oat, wheat, crimson clover, radish, and turnip. Control-1 was a fallow with herbicide application and control-2 was a fallow without herbicide application. DAP, days after cover crop planting

studies have found effective weed suppression by cover crop residues in the subsequent season when the cover crop produced biomass >6,000 kg ha^{-1} (Mohler & Teasdale, 1993). This supports the potential of the high biomass producing cover crops in this study (rye, the mixture of rye and crimson clover, and the mixture of five-a; their biomass ranged from 5,100 to 6,254 kg ha^{-1}) for effective weed suppression in the subsequent cash crop season under the absence of herbicide use. This advantage will result from an effective cover crop mulch, which will in turn depend upon the cover crop residue management. It should be noted that the present study estimated weed presence based on the percentage ground cover by weeds. Future studies are warranted to verify the results based on weed biomass or density.

The high biomass producing cover crops, rye, and the mixture of five-a and the other cover crops, the mixture of five-b, the mixture of oat and radish, and the mixture of crimson clover and turnip did not deplete more soil water than the fallow did (Table 4). The same results were obtained by our previous study in the upstate of South Carolina (St Aime et al.,

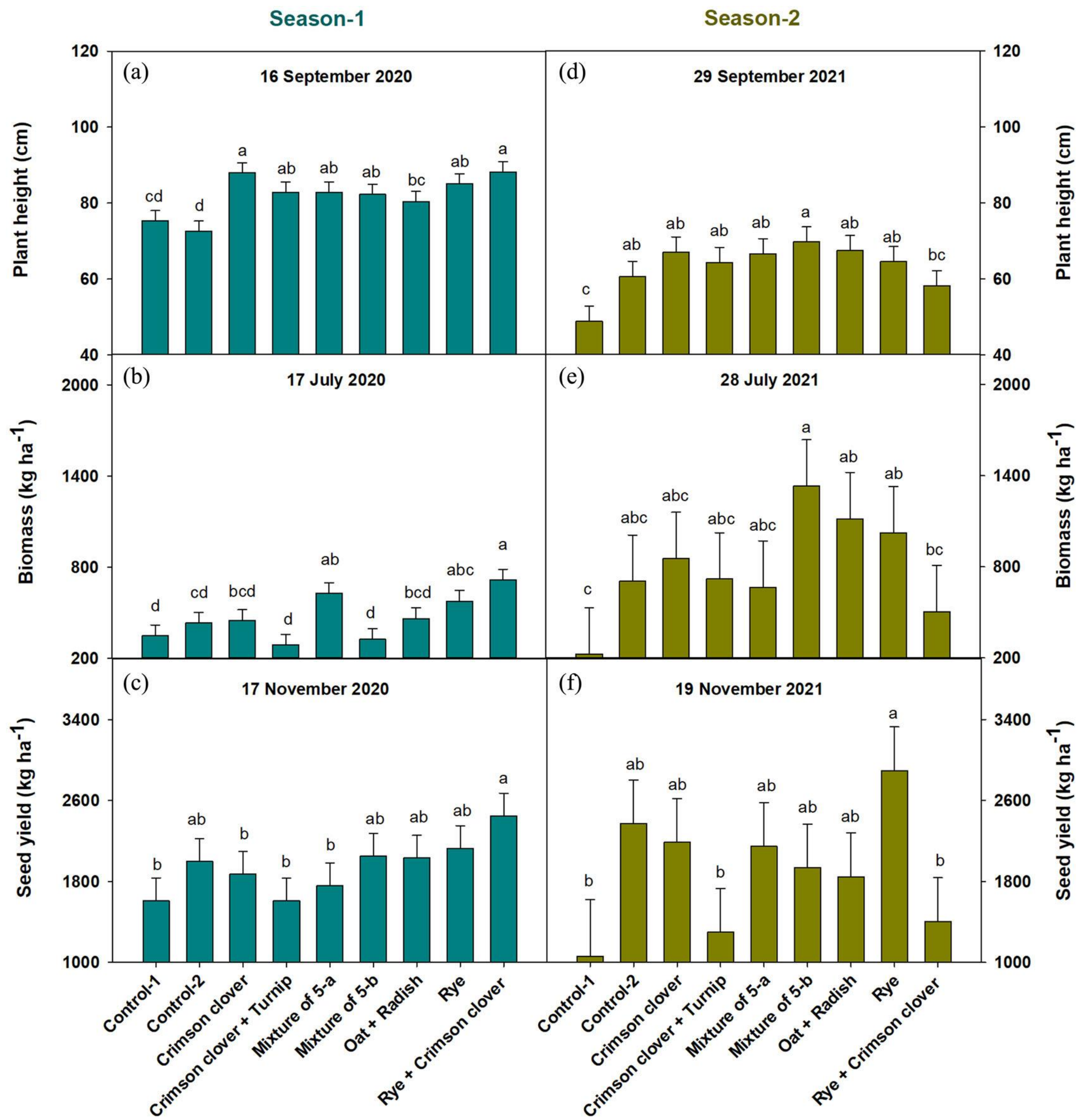

FIGURE 6 Effect of cover crop treatments on plant height, biomass, and seed yield of soybean in season-1 and season-2. Cover crops were terminated on 22 Apr. 2020 in season-1 and 28 Apr. 2021 in season-2. Soybean was planted at 50 and 58 d after cover crop termination in season-1 and season-2, respectively. Plant height was measured at 97 and 96 d after soybean planting in season-1 and season-2, respectively. Soybean biomass was measured at 36 and 33 d after soybean planting in season-1 and season-2, respectively. The soybean crop was at the vegetative stage when plant height and biomass were measured in both seasons. Soybean seed yield was measured at harvest maturity. Bars (least squares means) with different letters are significantly different according to the LSD test at $\alpha = .05$. Mixture of 5-a was a combination of Austrian winter pea, rye, crimson clover, hairy vetch, and oat. Mixture of 5-b was a combination of oat, wheat, crimson clover, radish, and turnip. Control-1 was a fallow with herbicide application and control-2 was a fallow without herbicide application

2020). Because the seasons in which that study was conducted received greater-than-normal rainfall for the region, it was not clear whether the same results (cover crops not depleting soil water for producing high biomass) will be obtained in dry years as well. Since the second season in the present study was drier than normal and we still did not see the stored soil water getting depleted in cover cropped plots than in fallow, the present study confirms the applicability of the observed results in dry as well as wet years. The equal amounts of stored soil water under cover crop treatments compared to a fallow in the present research might be a result of many factors. For example, improved infiltration and soil water retention due to possible improvements in soil physical properties through cover cropping (Blanco-Canqui et al., 2011, 2013; Chalise et al., 2018; Haruna et al., 2020; Hubbard et al., 2013; St Aime et al., 2020), an effect that would likely be increased in long-term cover cropping as organic matter is increased. Other reasons could be the suppression of evaporation and the conservation of soil moisture by the cover crop mulch (Clark et al., 1997; Daniel et al., 1999; Moschler et al., 1967; Russel, 1940; Unger & Vigil, 1998; Vann et al., 2018).

Cover crops can be effective in lowering soil penetration resistance due to many reasons such as the protection of surface soil aggregates against raindrop impact, better aggregation due to soil organic matter enrichment (Alvarez et al., 2017; Folorunso et al., 1992; Gabriel et al., 2021), and enhanced soil porosity through bio-pores formed by roots and increased earthworm activity (Lal et al., 1991). Generally, grass cover crops are more efficient in reducing soil penetration resistance than legume cover crops due to their greater biomass production and residue cover (Gabriel et al., 2021; Mupambwa & Wakindiki, 2012). In the present study, the cover crops that were the most effective in terms of reducing soil penetration resistance were single species of rye and the mixture of rye and crimson clover in which 75% of the total biomass was contributed by rye. Thus, their benefit on soil penetration resistance is likely a result of the quantity and quality of rye biomass and residue. The mixture of five-a, which was one of the three top biomass producers along with rye and the mixture of rye and crimson clover, did moderately well in terms of reducing penetration resistance; again, it might be a result of rye being the predominant component of that mixture. Interestingly, cover crop benefit on soil penetration resistance was not observed in the first season, indicating that it is a longer-term effect owing to organic matter enrichment.

Cover crops may affect soil respiration through a positive effect on microbial biomass, as most microbes produce CO_2 through aerobic respiration (Ward Laboratories, 2019). Substrate availability is proposed to regulate soil respiration such that the soil respiration increases with increases in the available C to microbes (Curiel Yuste et al., 2007; M. I. Khan et al., 2018). Thus, the higher WEOC (available C to microbes) in the soil covered with the mixture of five-a (Figure 5), compared to that under fallow might be a major reason behind the higher respiration values in the soil covered with the mixture of five-a. The lower soil respiration values in season-1 regardless of the cover crop treatments may be an indication of the poor soil health that might be a result of the historically conventional land management practices (including conventional tillage and no cover cropping) on the land that was used for this study. The above results should be interpreted after taking into consideration that the measurement protocol, the Haney test, is still undergoing field evaluation and refinement in contrasting soils and climates across the United States. However, multiple recent reports support the usefulness of this test to characterize soil health (Ansley et al., 2021; Bavougian et al., 2019; Mattila & Rajala, 2022). Bavougian et al. (2019) reported the appropriateness of the Haney soil health test for quantifying the effects of a change in management such as cover cropping to replace fallow periods in annual systems.

Many producers are still concerned whether the use of soil water and nutrients by winter cover crops may negatively affect the performance of the subsequent summer cash crops. Our results do not support this concern as soybean plant height, biomass, and seed yield were never decreased when the soybean crop followed any of the seven cover crops evaluated in this study (Figure 6). Furthermore, rye and the mixture of five-a generally improved soybean performance, compared to a chemical fallow.

Considering biomass production, weed suppression, and improvements in soil health and the following soybean crop performance, rye, the mixture of five-a, and the mixture of rye and crimson clover turned out to be the best cover crops for the clayey soils in South Carolina. Even though half of the biomass production of the mixture of five-a was contributed by rye, the other half was equally distributed among another grass species (oat) and three legumes (Austrian winter pea, crimson clover, and hairy vetch). Recently, winter pea has been found to be a potential winter legume cover crop for the Southeast, and the regional breeding programs are now focusing on improving its adaptability (Vann et al., 2019, 2020). Crimson clover and hairy vetch are both commonly used legume cover crops in the southeastern United States and are popular for their high biomass production (Vann et al., 2016, 2021). However, when used as a sole crop, crimson clover can have notably slower N release than other legume cover crops and can even lead to N immobilization (Reberg-Horton et al., 2012). Recent research has found oat to be a suitable species to be mixed with crimson clover and winter pea for enhancing the biomass production of the mixture and improving C/N ratio in the soil (Vann et al., 2019). Additionally, oat is less susceptible to Hessian fly damage (reviewed in Vann et al., 2019), which is a major pest in the Southeast. Our results suggest that the mixture of five-a that combines the above legumes and oat with rye (one of the highest biomass-producing cover crops in the Southeast), might be a soil health-building cover crop for the region.

The present study demonstrated an advantage of cover cropping over a chemical fallow (control-1). Rye, the mixture of rye and crimson clover, the mixture of five-a, the mixture of five-b, and the mixture of oat and radish were as effective as herbicide application in terms of weed suppression (Figure 3). The chemical fallow never had the advantage of storing more soil water, compared to any of the cover crops tested in this study as well as a fallow without herbicide control (Table 4). Two years of cover cropping had a positive effect on reducing penetration resistance as the penetration resistance was lower under cover crops than under a chemical fallow in the 2nd year. The chemical fallow was inferior to the mixture of five-a considering the soil biological activity (Figure 5). Finally, the plant height, biomass, and seed yield of the soybean crop were lower when grown after a chemical fallow than the mixture of five-a, rye, and/or the mixture of rye and crimson clover (Figure 6). Taken together, our results provide the rationale for farmers to plant any of the cover crops identified in this study (rye, the mixture of five-a, and the mixture of rye and crimson clover) in the clayey soils of the Southeast rather than keeping the land under a chemical fallow during the fall–winter season.

5 | CONCLUSIONS

Weed suppression is one of the most sought-after short-term benefits of cover crops, which is often correlated with cover crop biomass production. Rye is one of the highest biomass-producing cover crops grown in the southeastern region. Due to the same reason, it is one of the most commonly grown cover crops in the same region. In the present study, we found two grass–legume cover crop mixtures, the mixture of rye and crimson clover and the mixture of five-a (Austrian winter pea, rye, crimson clover, hairy vetch, and oat), that produced the same amount of biomass as that of rye. Both mixtures contained rye as the predominant component (75% in the two-species mixture and 50% in the five-species mixture). The high-biomass producing cover crops, rye, the mixture of five-a, and the mixture of rye and crimson clover did not deplete more soil water than a fallow did. They controlled weeds equally well or better than herbicides during the cover crop growing period. They also reduced soil penetration resistance in the second season. The mixture of five-a, which is a combination of two grasses and three legumes, also improved soil biological activity, compared to a fallow. Overall, our results suggested that rye, the mixture of five-a, and the mixture of rye and crimson clover will be suitable winter cover crops for the clayey soils in the Southeast based on biomass production, weed suppression, and improvements in soil health and the following soybean crop performance. The above results provide the rationale for farmers to plant cover crops rather than keeping the land under a chemical fallow during the fall–winter season.

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AUTHOR CONTRIBUTIONS

Ricardo St Aime: Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – original draft; Writing – review & editing. William C. Bridges, Jr.: Formal analysis; Methodology; Validation; Writing – review & editing. Sruthi Narayanan: Conceptualization; Data curation; Formal analysis; Funding acquisition; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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