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Can adoption of multispecies cover crop mixtures improve soil water movement in fragipan soils of southern Illinois?

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Abstract

Crop production on fragipan soils can be severely limited due to restrictive root growth and perched water table. We hypothesized that roots of multispecies cover crop mixtures containing annual ryegrass (ARG, *Lolium multiflorum L.*), hairy vetch (*Vicia villosa*), and crimson clover (*Trifolium incarnatum*) can improve soil physical conditions for main crop root growth, and roots of ARG can penetrate through the fragipan layer to remove excess moisture. Two on-farm sites, Marion and Springerton, in southern Illinois were established in 2019 and 2013, respectively. Depth from surface to fragipan layer was 70 cm and 50 cm for Marion and Springerton, respectively. Both sites had replicated trials in a corn (*Zea mays* L.)–soybean (*Glycine max* L. Merr.) rotation with two treatments: with cover crop (CC) and without cover crop (NCC) mixes having ARG as the dominant species. In spring of 2023, intact soil cores were collected and analyzed for soil water retention characteristics and particle size distributions. Volumetric water contents (VWCs; $cm^3\ cm^{-3}$) of the soil through 90-cm depth were monitored during corn phase and during cover crop growth of 2023–2024. At Marion, NCC had higher VWC at 25- and 55-cm depths than CC most of the time during summer. At Springerton, CC soils within 15- to 35-cm depths had higher VWC than NCC during cover crop growth in winter. Inclusion of cover crop mixtures can improve soil water movement, but the magnitude depends on the length of adoption and depth to the fragipan layer.

Plain Language Summary

Fragipan soils are compacted layers below the soil surface that restrict root penetration and water movement. Roots of annual ryegrass have been observed to penetrate fragipan and improve water flow through soil. This study was conducted to determine the long-term effects of planting mixed cover crop species after harvest of the main crop on soil properties and changes in soil water content. Two Illinois fields, one at

Abbreviations: ARG, annual ryegrass; CC, cover crop; FC, field capacity; NCC, no cover crop; PAW, plant available water; PWP, permanent wilting point; VWC, volumetric water content.

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Marion and another at Springerton with fragipan layers at 70 cm and 50 cm, respectively, were selected for this study. At Marion, no cover crop treatment had higher water content than cover crop at 25- and 55-cm soil depths during summer probably due to cover crop water uptake from these depths. Growing cover crop mix increased soil water storage during winter at Springerton only. These results will be useful to improve crop production under fragipan soils.

1 | INTRODUCTION

The presence of a restrictive soil layer/horizon like a fragipan in the soil profile poses a significant problem in root penetration and water movement; hence, crop growth and production suffer from extreme hydrologic conditions (Rhoton, 1990; Graveel et al., 2002). Over 11 million ha of soils have fragipan as their subsoil horizon, and these soils are spread extensively across Pennsylvania, Mississippi, New York, Missouri, and Kentucky, and sparsely in Arkansas, Illinois, Ohio, Indiana, and Tennessee (Bockheim & Hartemink, 2013). These soils normally have a perched high-water table in the winter and early spring, leading to excess soil water and shallow rooting (McDaniel et al., 2008). In the summer, because of a limited rooting depth, crops are prone to drought conditions under high evapotranspiration demands. Plant roots modify soil hydraulic and physical properties such as bulk density (BD), pore size distribution, and reorganization of soil particles through root penetration and expansion, as well as shrinkage or decay forming macropores (Lu et al., 2020; Ogilvie et al., 2021). Fragipan soils offer special opportunities to study cover crop effects on soil water availability. Fragipans are impermeable to roots and water, and where they are at shallow depths, their breakage would provide cover crop roots access to deeper water reserves and a greater effective soil volume. Adoption of annual ryegrass (ARG, *Lolium multiflorum L.*) as a cover crop has been shown to solubilize cementing agents in the upper part of fragipan layer (Matocha et al., 2018). The overarching objective of this on-farm study is to determine whether the adoption of multispecies cover crop mix which includes ARG can improve drainage in fragipan soils through increasing soil porosity.

Soil water and physical properties such as BD and texture being linked to water storage and movement, can be critical factors in crop production. In the US system of soil taxonomy, the fragipan is described as a land use limiting horizon with very low soil water permeability that limits root penetration (Drohan et al., 2020). In southern Illinois, fragipans are more common in acidic soils with less than 30% clay and less than 12% slope (Smeck et al., 1989; Franzemeier et al., 1989). These soils are deeply weathered with argillic horizons and clay fractions dominated by kaolinite with lesser amounts of 2:1 phyllosilicates (Wilson et al., 2010). Some fragipan layers develop secondary cementation through the dehydration of hydrous metal oxides, forming a film around primary soil particles, which slake when wet and become very hard during drying (Hamblin, 1986). Fragipans exhibit lower saturated hydraulic conductivity than overlying soil horizons, which can cause water to accumulate and thereby creating a perched zone of saturation (Calmon et al., 2015). Any water transmission through fragipan horizons may take place through the bleached gray seams that isolate the polygon structural unit; sometimes these seams are plugged with illuviated clay (Rhoton & Römkens, 1998). Upward water movement may occur if a strong hydraulic gradient develops between the fragipan and the soil surface. The presence of a fragipan layer at shallow depth (approximately within 50 cm from the surface) is highly detrimental to crop growth, particularly under extreme precipitation patterns (Graveel et al., 2002). A plant can rapidly deplete available soil water above the fragipan layer, which leads to severe water stress unless timely precipitation occurs (Unger & Kasper, 1994). In southern Illinois, a water balance indicates a surplus of water in fragipan profiles from December through May, a period when 54% of the annual precipitation is received as both snow and rain (Wilson et al., 2010). A resulting rise of the water table occurs during fall and early spring, appears to be mainly dependent on (1) amount of precipitation, (2) transpiration rate, and (3) rate of water movement in the fragipan and the underlying glacial till (Gile, 1958).

Winter cover cropping influences the soil water relationship of summer crops by (1) reducing evaporation due to mulch from cover crop residues, (2) increasing water infiltration, and (3) uptake of soil water by transpiration (Unger & Vigil, 1998). The net effect of a cover crop on the soil water demand of the succeeding summer crop depends on the timing and amount of precipitation, infiltration rate, and water use by the cover crop for evapotranspiration (Unger & Vigil, 1998). Garba et al. (2022) reported that a minimum annual precipitation of 700 mm represents a break-even point to achieve yield benefits (of the main crop) from cover cropping under dryland conditions. In maize–soybean rotations in the US Midwest, researchers (Daigh et al., 2014; Basche et al., 2016) observed that use of a cereal rye (*Secale cereale*) as a cover crop did not significantly lower soil water content; moreover, cover crop significantly increased the field capacity (FC) water content by 10%–11% and plant available water (PAW) by 21%–22% (Basche et al., 2016). Specifically, at the two field sites

studied by Chatterjee et al. (2024), winter cover crop mixes were planted in field-long strips on a corn–soybean rotation. Benefits of cover cropping to corn grain yields in these long-term trials began only when ARG was inserted into the cover crop mix (data not shown). The mix at one site of ARG, cereal rye (*S. cereale*), and hairy vetch was designed to gather benefits from each of species, and the intent of the ARG was to break the fragipan (Sustainable Agriculture Research and Education, 2019). According to Plumer (2014), fibrous roots of ARG under fragipan soils can reach up to 70- to 150-cm depth, whereas roots of hairy vetch are limited to only 40 cm. Karathanasis et al. (2014) proposed a mechanism that roots of ARG having high sodium soluble ratio penetrate into fragipan capillaries and generate critical swelling pressure and shearing stress required to rupture the fragipan. Channels and macropores formed by ARG roots may provide access through the dense subsurface layer, so that subsequent plant rooting and water movement are improved (Unger & Kasper, 1994). Hence, we submit that the inclusion of ARG in cover crop mixtures may well have special activity in fragipan breakage and improved water movement.

For this study, we selected two on-farm experiments at two locations in southern Illinois, Marion established in 2019 and Springerton established in 2013. Both experiments were initiated by growers to overcome the yield limitation under fragipan soils through adoption of three-way cover crop mix, ARG–vetch–clover. In a previous manuscript from this study (Chatterjee et al., 2024), we compared soil physical properties based on conventional soil depth increments (15 cm) without considering the depth of fragipan. We used processed soil samples to study the soil water retention characteristics and measured soil water content during the soybean phase only for the Springerton site. For this manuscript, we adjusted our soil sampling depth increments considering the depth of fragipan horizon and conducted soil water retention characteristics using undisturbed soil core. Moreover, we repeated soil moisture measurements during the corn phase because we expected a significant difference in soil moisture use by corn because of its deeper rooting depth and greater water demand. Finally, for this study, we studied changes in soil moisture content through profile (90-cm depth) at 10-cm depth increment, and soil water storage was studied during the corn phase (summer), June–September of 2023, and cover crop growth phase (winter), December 2023–March, 2024.

Core Ideas

- Cover crops roots can improve the physical condition of fragipan soils.
- Cover crops' roots accelerate eluviation of silt particles at fragipan layer.
- For one site, cover crops reduced water content at 25- and 55-cm depths in summer.
- For another site, cover crops increased water storage in winter.

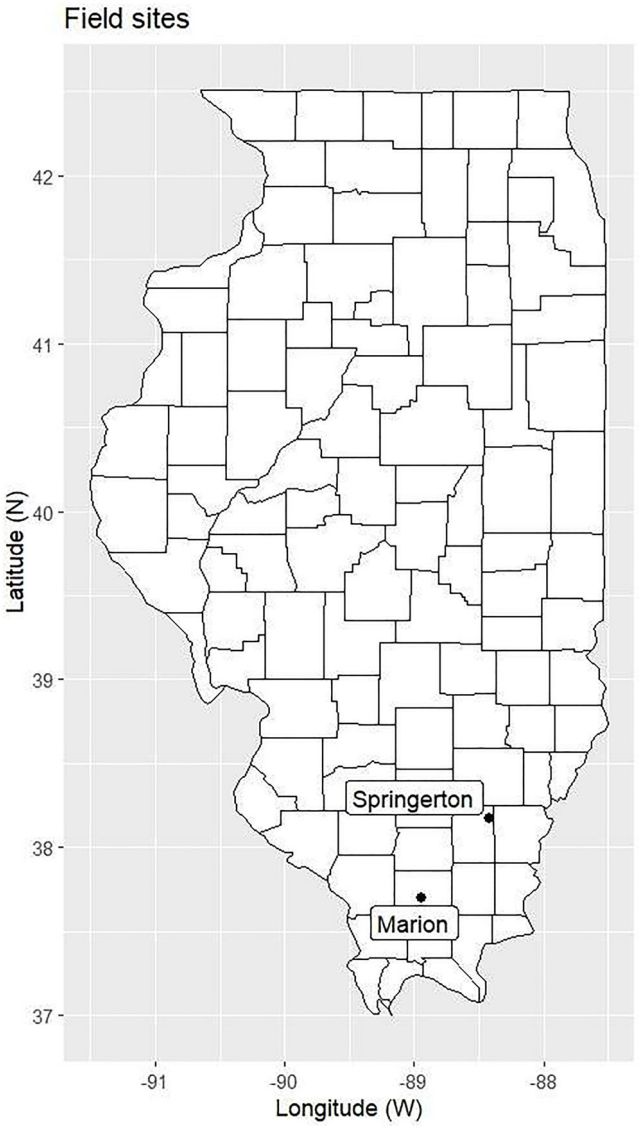


FIGURE 1 Location of two on-farm sites in Illinois selected for this study.

2 | MATERIALS AND METHODS

Two on-farm experiments, near Marion (37.70, −88.94) and Springerton (38.17, −88.42) in southeast Illinois (Figure 1), were used for this study. The climate is characterized as humid subtropical. The Marion site soil is classified as a fine-silty, mixed active, mesic Fragic Oxyaquic Hapludalf belonging to the Rend soil series, and the Springerton soil is classified as

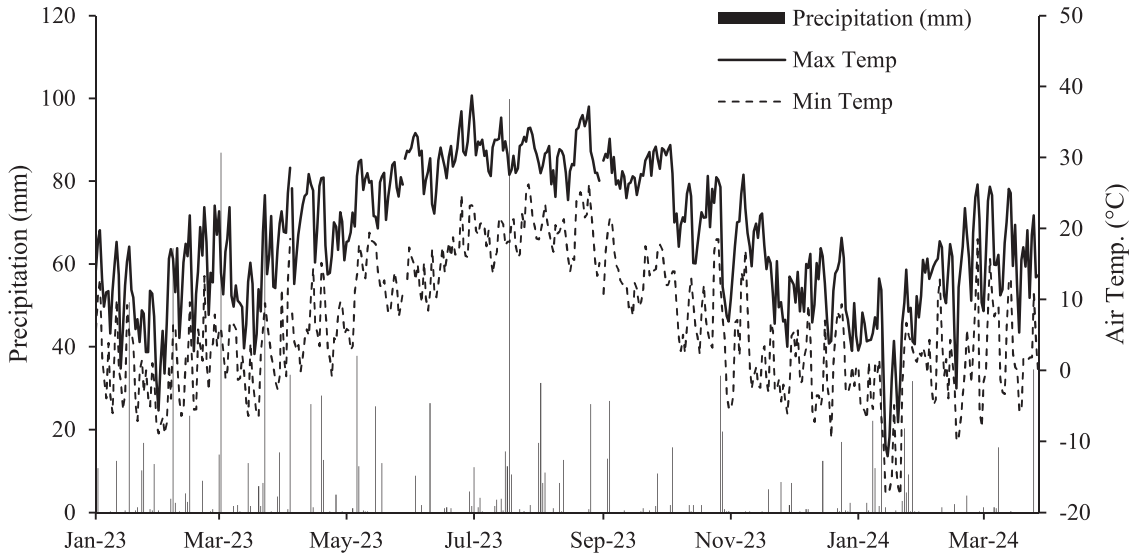


FIGURE 2 Daily precipitation (mm) and maximum and minimum air temperature (°C) from January 2023 to March 2024, collected from the nearest weather station (Carbondale, IL).

fine Smectitic, mesic Aeric Fragic Epiaqualf of the Bluford soil series. At Marion, soil profile had an Ap horizon from 0- to 20-cm depth, Bt horizon from 19- to 45-cm depth, Bt/E horizon from 45- to 54-cm depth, E horizon from 54- to 63-cm depth, E/Btx horizon from 63- to 70-cm depth, and Btx horizon (fragipan layer) from 70- to 120-cm soil depth (Chatterjee et al., 2025). At Springerton, soil profile had an Ap horizon from 0- to 10-cm depth, Bt horizon, 10- to 31-cm depth, E horizon from 31- to 42-cm depth, E/Btx horizon from 42- to 50-cm depth, and Btx horizon from 50- to 120-cm soil depth (Chatterjee et al., 2025).

Daily precipitation and maximum and minimum air temperatures from January 1, 2023, to March 27, 2024, are collected from the weather station nearest to both sites (Water and Atmospheric Resources Monitoring Program, 2024) and presented in Figure 2. Normal air temperature and rainfall values correspond to 35-year (1989–2023) average data (Illinois Soil Water Survey, 2024). Annual precipitation in 2023 was 1178 mm, close to normal (1132 mm). January of 2023 and 2024 received more than normal precipitation, +69 and +88 mm, respectively. March of 2023 was extremely wet (+120 mm above normal), but March of 2024 was dry (−46 mm below normal). June of 2023 had less than normal precipitation (−54 mm), July and August were above normal (+71 and +40 mm, respectively), and September had less than normal precipitation. During the growing season (June–September, 2023), maximum monthly average air temperature was close to 35 year average (+0.54°C, −0.07°C, −0.76°C, and +1.65°C, respectively), but minimum air temperature was cooler than normal (−8.28°C, −5.90°C, −5.20°C, and −5.9°C, respectively).

At each site, long strips of ∼300–400 m length and 3 m width at Marion and 24 m width at Springerton of two treatments, one with cover crop (CC) and one without cover crop (NCC), were established in 2019 at Marion and in 2013 at Springerton. Corn (*Zea mays* L.)–soybean (*Glycine max* L. Merr.) phases were synchronized at both sites. Both fields were under no-tillage. Fields were under the corn phase during 2015, 2017, 2019, 2021, and 2023, and under the soybean phase during 2014, 2016, 2018, 2020, and 2022. A cover crop mix containing ARG with a seeding rate of 6.7 kg ha^{-1}, and hairy vetch (*Vicia villosa*) and crimson clover (*Trifolium incarnatum*) were planted at the rate of 4.5 kg ha^{-1} during fall after harvest of the soybean crop.

Volumetric soil water contents (cm^3 cm^{-3}) were measured using a capacitance-based Sentek "Drill and Drop" moisture probe (Sentek Sensor Technologies) with a tapered design having a length of 90 cm. Each probe had a moisture sensor at 5-, 15-, 25-, 35-, 45-, 55-, 65-, 75-, and 85-cm depths. Each soil moisture probe was powered by a rechargeable battery connected to a solar panel housed in the network station, which was mounted on tripods. Weatherproof Campbell Scientific instrument enclosures were used to house the wiring and batteries. Data from the soil moisture probe were transferred to a CR-1000 datalogger (Campbell Scientific). Dataloggers were on-site networked via 900 MHz spread-spectrum radio (Campbell RF407, Campbell Scientific). Networked stations were remotely accessed with a CELL210 cellular modems (Campbell Scientific). The soil moisture probes were installed after corn planting and herbicide application on June 27, 2023, and moisture data were collected until September 22, 2023 (before harvest); this phase is referred as "summer". Again, soil moisture sensors were reinstalled on November 29, 2023 (after harvest and cover crop planting) and continued until March 27, 2024; this phase is referred as "winter". Hourly volumetric water content (VWC) values (output from data loggers) were converted to a daily value by average. Daily soil water storage value was

TABLE 1 Changes in soil physical properties in response to with (CC) and without (NCC) cover crops within soil profiles having fragipan layer at two on-farm sites located in southern Illinois. Bold letters indicate significant differences between treatments at the same soil depth and site at 90% significance level

Site	Depth (cm)	Cover	Bulk density (Mg m^{-3})		Sand	Silt (g kg^{-1})	Clay	Texture	SAT (cm^3 cm^{-3})	FC (cm^3 cm^{-3})	PWP (cm^3 cm^{-3})	PAW (cm^3 cm^{-3})
Marion	0–5	NCC	1.39	(0.24)a	53 (9.6)a	742 (6.2)a	205 (4.7)a	SL	0.38 (0.02)a	0.23 (0.02)a	0.10 (0.03)a	0.13 (0.04)a
		CC	1.40	(0.10)a	55 (0.6)a	743 (6.4)a	202 (5.7)a	SL	0.39 (0.02)a	0.25 (0.01)a	0.11 (0.03)a	0.14 (0.03)a
	25–30	NCC	1.55	(0.14)a	42 (18.2)a	705 (16.3)a	253 (7.5)a	SL	**0.40 (0.06)b**	0.31 (0.04)a	0.11 (0.09)a	0.18 (0.04)a
		CC	1.43	(0.17)a	39 (6.2)a	710 (18.2)a	251 (18.1)a	SL	**0.48 (0.03)a**	0.38 (0.07)a	0.14 (0.08)a	0.24 (0.09)a
	75–80	NCC	1.48	(0.09)a	26 (8.5)a	**735 (19.7)b**	239 (13.5)a	SL	0.48 (0.02)a	0.34 (0.10)a	0.16 (0.06)a	0.20 (0.01)a
		CC	1.45	(0.05)a	21 (3.3)a	**753 (16.1)a**	226 (13.3)a	SL	0.48 (0.03)a	0.27 (0.04)a	0.15 (0.03)a	0.12 (0.07)a
Springerton	0–5	NCC	**1.37**	**(0.18)a**	116 (5.91)a	667 (25.4)a	217 (20.8)a	SL	**0.39 (0.03)b**	0.24 (0.05)a	**0.09 (0.02)a**	0.15 (0.03)a
		CC	**1.21**	**(0.14)b**	134 (4.54)a	661 (39.8)a	205 (10.4)a	SL	**0.44 (0.03)a**	0.26 (0.03)a	**0.06 (0.02)b**	0.20 (0.05)a
	25–30	NCC	1.50	(0.06)a	58 (3.43)a	675 (24.6)a	267 (12.5)a	SL	**0.50 (0.02)a**	**0.43 (0.03)a**	**0.18 (0.03)a**	0.26 (0.06)a
		CC	1.52	(0.08)a	69 (4.05)a	668 (25.4)a	263 (20.9)a	SL	**0.40 (0.05)b**	**0.33 (0.04)b**	**0.13 (0.04)b**	0.20 (0.05)a
	75–80	NCC	1.52	(0.10)a	**51 (8.5)a**	**669 (25.8)b**	280 (5.1)a	SCL	0.44 (0.05)a	0.36 (0.04)a	0.21 (0.03)a	0.15 (0.05)a
		CC	1.48	(0.07)a	**24 (3.3)b**	**697 (11.3)a**	279 (7.8)a	SCL	0.44 (0.03)a	0.34 (0.05)a	0.22 (0.01)a	0.13 (0.06)a

Note: Different small letters within the same depth indicate significant difference between mean values of CC and NCC at $p = 0.10$. Value in bracket indicates standard deviation.
Abbreviations: FC, field capacity; PAW, plant available water; PWP, permanent wilting point; SAT, saturated water content; SCL, silty clay loam; SL, silt loam.

calculated by the summation of multiplying the VWC values with respective depth (cm) increments of sensor.

Soil core samples of ~120-cm depth were collected from each plot using a hydraulic probe in line with a plastic sleeve of a diameter of 7.62 cm on November 28, 2023. Soil core samples of specific 5-cm depth increments, namely 0–5 cm, 25–30 cm, and 75–80 cm were used to generate soil water retention curve using the evaporation method by the HYPROP instrument (Meter Group). Depth increments were selected to characterize soil at the surface (0–5 cm), just above the fragipan layer within 25–30 cm (Bt horizon), and the fragipan layer (Btx) within 75- to 80-cm depth. For this method, soil cores were saturated by immersing cores in degassed, 0.01 M $CaCl_2$ solution. HYPROP provides suction inside the soil core at two different depths and measures weight loss over drying of saturated soil cores at 10-min intervals. Following the HYPROP measurements, soil water retention between 10^3 and 10^6 cm was determined using the WP4C instrument (Meter Group). LABROS Soilview Analysis software (Meter Group) was used to analyze the soil water retention characteristic curve. Soil water retention characteristic curve was fitted using a bimodal constrained van Genuchten model fit (Durner, 1994). The van-Genuchten equation is expressed in the following equation, where h (cm) is pressure head; θ, θ_r, and θ_s (cm^3 cm^{-3}) are the current, residual, and saturated water contents; α (cm^{-1}), n (-), and m (-) are empirical parameters.

$$\theta\ (h) = \theta_r + \frac{\left(\theta_S - \theta_r\right)}{\left(1 + (\alpha h)^n\right)^m} \quad (1)$$

Based on the retention curve fit, soil water content at saturation (SAT), FC (at 330 cm), and permanent wilting point (PWP; 15,000 cm) were determined. PAW content was determined by the difference in soil water content between FC and PWP.

Soil particle size analyses: Particle size distribution was determined from a well-dispersed slurry of soil in a sodium hexametaphosphate solution. The sand was removed and collected by wet sieving using a 53-μm mesh sieve. Silt and clay were determined with a particle size analyzer (Cilas Particle Size Analyzer (PSA) model 1190) (CPS US Inc.) using 6 μm as the silt-clay cutoff (Faé et al., 2019). The collected dried sand fraction was separated using dry sieving.

Statistical analysis and model fitting were carried out using "SAS Studio On Demand" for Academics (https://welcome.oda.sas.com/, SAS Institute Inc.). Changes in soil water at each depth over time were analyzed using the split-plot in time approach for the repeated measure analysis. A linear mixed model was fitted and summarized using the proc mixed and proc plm procedures. A "First order autoregressive" structure was used for the covariance estimate. The denominator

TABLE 2 *p*-values for the main effects of cover crop (CC) and day of observation (Day) and their interaction (CC × Day) on volumetric soil water content (cm cm^{-3}) collected during 2023–2024 at nine soil depths within 85-cm depth of soil profile having fragipan layer at two on-farm sites located in southern Illinois. Bold letters indicate significant differences in soil water content between treatments at the same depth and site at 90% siginificance level for interaction effect

Depth (cm)	Marion			Springerton		
	CC	Day	CC × Day	CC	Day	CC × Day
5	0.85	<0.01	0.20	0.06	<0.01	0.74
15	0.17	<0.01	0.20	0.01	<0.01	**<0.01**
25	0.10	<0.01	**0.01**	0.21	<0.01	**<0.01**
35	0.99	<0.01	0.10	0.08	<0.01	**<0.01**
45	0.83	<0.01	1.00	0.01	<0.01	0.35
55	0.17	<0.01	**0.01**	0.05	<0.01	1.00
65	0.05	<0.01	1.00	0.65	<0.01	1.00
75	0.64	<0.01	1.00	0.89	<0.01	1.00
85	0.19	<0.01	1.00	0.65	<0.01	1.00
Soil water storage	<0.01	<0.01	1.00	<0.01	<0.01	<0.01

degrees of freedom were estimated using the Kenward–Roger method 2. Treatment × date interaction component was used to compare means for the specific date determined by the "sliceby = date" argument. Mean differences were compared at a 90% significance level.

3 | RESULTS

3.1 | BD, texture, and soil water retention parameters

At the Springerton site, CC had significantly lower soil BD value by 11.7% at 0- to 5-cm depth compared to NCC (Table 1). However, the effect was only limited to the surface, both treatments had similar BD values at deeper soil depths. Marion site had silt loam texture throughout the profile, whereas Springerton had silt loam within 0- to 5-cm and 25- to 30-cm depths and silty clay loam within 75- to 80-cm depth. Although CC and NCC had similar soil textural classes, both the sand and silt contents differed between the two treatments within 75- to 80-cm soil depth. At both sites CC had lower sand content and higher silt content compared to NCC within 75–80 cm.

Soil water content values at SAT, FC, and PWP, levels showed CC had a more pronounced effect on soil water retention at Springerton over Marion (Table 1). At Marion, CC had higher saturated water content than NCC within 25–30 cm. In Springerton, CC had higher saturated water content than NCC, and CC had lower water content at wilting point than NCC within 0- to 5-cm depth. However, within 25- to 30-cm depth, CC had lower soil water content than NCC at SAT, FC, and PWP.

3.2 | Volumetric soil water content and soil water storage

We collected 88 days of soil water content observations during corn growing season (June 27 through September 22, 2023) and 120 days of soil water content observations after corn harvest and during cover crop growth (November 29, 2023, through March 27, 2024), at nine soil depth increments within 90-cm soil depth (Figures 3–5). We observed significant differences in soil water content between NCC and CC treatments during the summer months at Marion and during the winter months at Springerton (Table 2).

At Marion, soil water content at 25- and 55-cm depths were significantly responded to interactions between observation day and cover crop treatment ($p < 0.10$) (Table 2; Figures 3 and 5). A 25-cm depth, NCC had higher soil water content than CC soils during most of the summer months, 26 days in July, 20 days in August, and all 22 days of observation in September. Similarly at 55-cm depth also, NCC had higher soil water content than CC from June 27 through July 2, from August 1 through August 4, and from August 22 through August 29.

At Springerton, soil water content at 15-, 25-, and 35-cm depths was significantly responded to interactions between observation day and cover crop treatment ($p < 0.10$) (Table 2; Figures 4 and 5). At 15-, 25-, and 35-cm depths, CC soils had significantly ($p < 0.10$) higher soil water content than NCC soils during winter months. At 15-cm soil depth, CC had higher soil water content than NCC for 21 days in December, first 7 days in January, 19 days in February, and 21 days in March. At 25-cm soil depth, CC had higher soil water content than NCC for 18 days in December, only 1 day in February, and 3 days in early March. At 35-cm soil depth, CC had higher

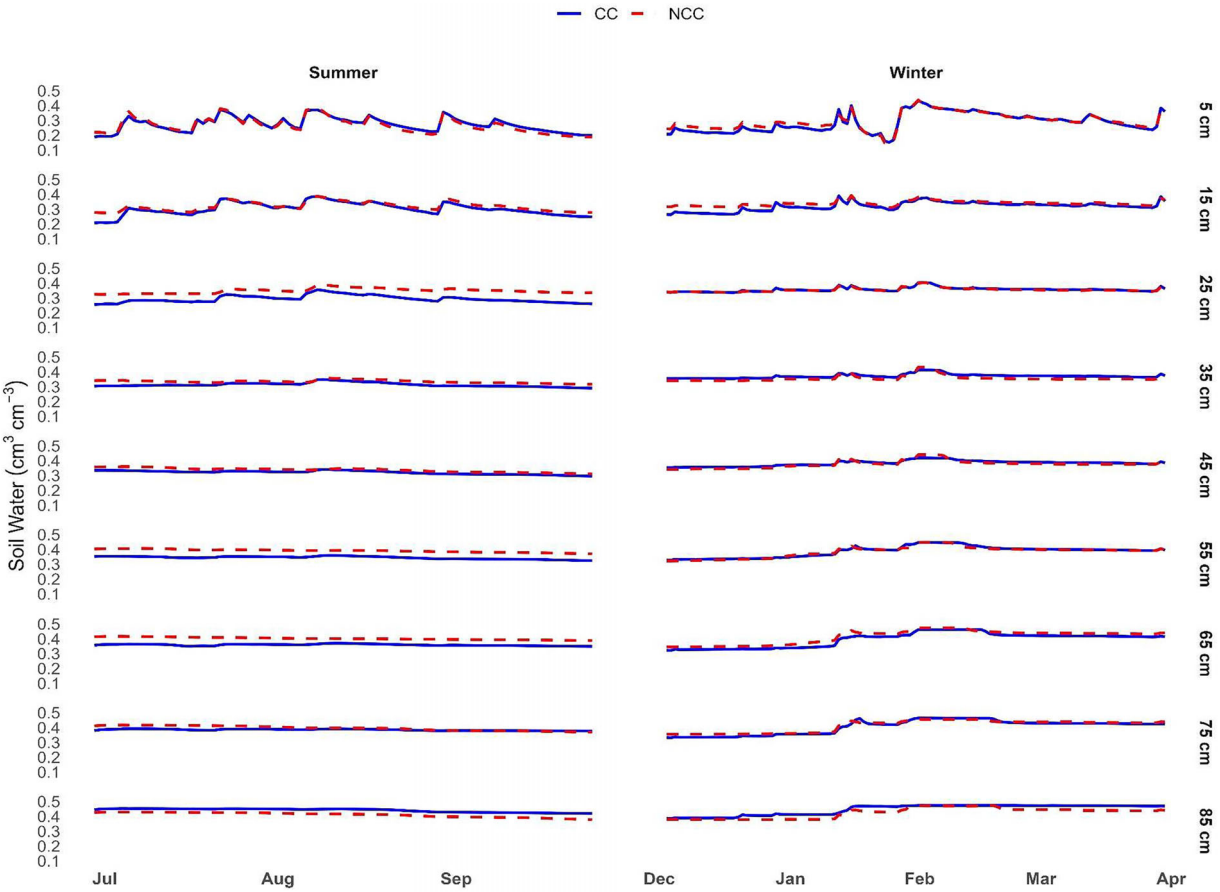


FIGURE 3 Changes in volumetric soil moisture content at nine soil depths from June 27, 2023 to September 22, 2023, in the left panel and from November 29, 2023, to March 27, 2024, in the right panel for with (CC) and without (NCC) cover crop at the Marion, IL site.

soil water content than NCC for 17 days in December, 3 days in January, and 12 days in March.

At Marion, NCC and CC had similar soil water storage throughout observation period (Table 2; Figure 6). At Springerton, NCC and CC had significant differences in soil water storage ($p < 0.01$) (Table 2; Figure 6). At Springerton, CC soils had significantly higher soil water storage than NCC soils mostly limited to winter months, 3 days in December of 2023 and 6 days in January, 2 days in February, and 9 days in March of 2024.

4 | DISCUSSION

Our results suggest that the influences of cover crops on soil physical properties, water retention, and soil water movement varied between two sites. Major differences between two sites are (1) depth to fragipan and (2) time length under cover crop management. Springerton had the Btx horizon close to surface (50 cm) compared to Marion (70 cm). The cover crop management was established at Springerton 6 years prior to Marion. Interaction between these two factors might have influenced differences in cover crop response between two sites. Depth to fragipan controls the susceptibility of plant growth to water stress. Previous studies (Bradford & Blanchar, 1977, 1980; Frye et al., 1983; Rhoton, 1990) showed that depth to fragipan explains the grain yield variability. This might explain that although fragipan was close to surface but growth of cover crops over 6 years lead to a more prominent effect at Springerton compared to Marion.

At Springerton, the adoption of CC reduced the soil BD at 0- to 5-cm depth. Roots of cover crop mix can have higher rooting density and more biomass storage in fine roots, which influences the pore size distribution compared to main crops, corn, and soybean (Bodner et al., 2014; Lu et al., 2020; Ogilvie et al., 2021). Fine roots realigned sand grains along their axis, and big roots make their path by breaking the weak arrangement of grains (Phalempin et al., 2021). Although ARG roots can grow down to 1 m (Kristensen & Thorup-Kristensen, 2004; Steynberg et al., 1994), but in dense soil horizons (Bt and Btx) of deeper depths, where microporosity is low and dominated by isolated pores, root growth might lead to high mechanical resistance (Lucas et al., 2019).

Both, fragipan soils commonly have a silt loam texture at most depths. Like Sheppard et al. (2024), we also found a high silt content, low sand content, and a range in clay percentage between 202 and 208 g kg^{-1}, across all depth increments. We observed a consistently higher silt content for

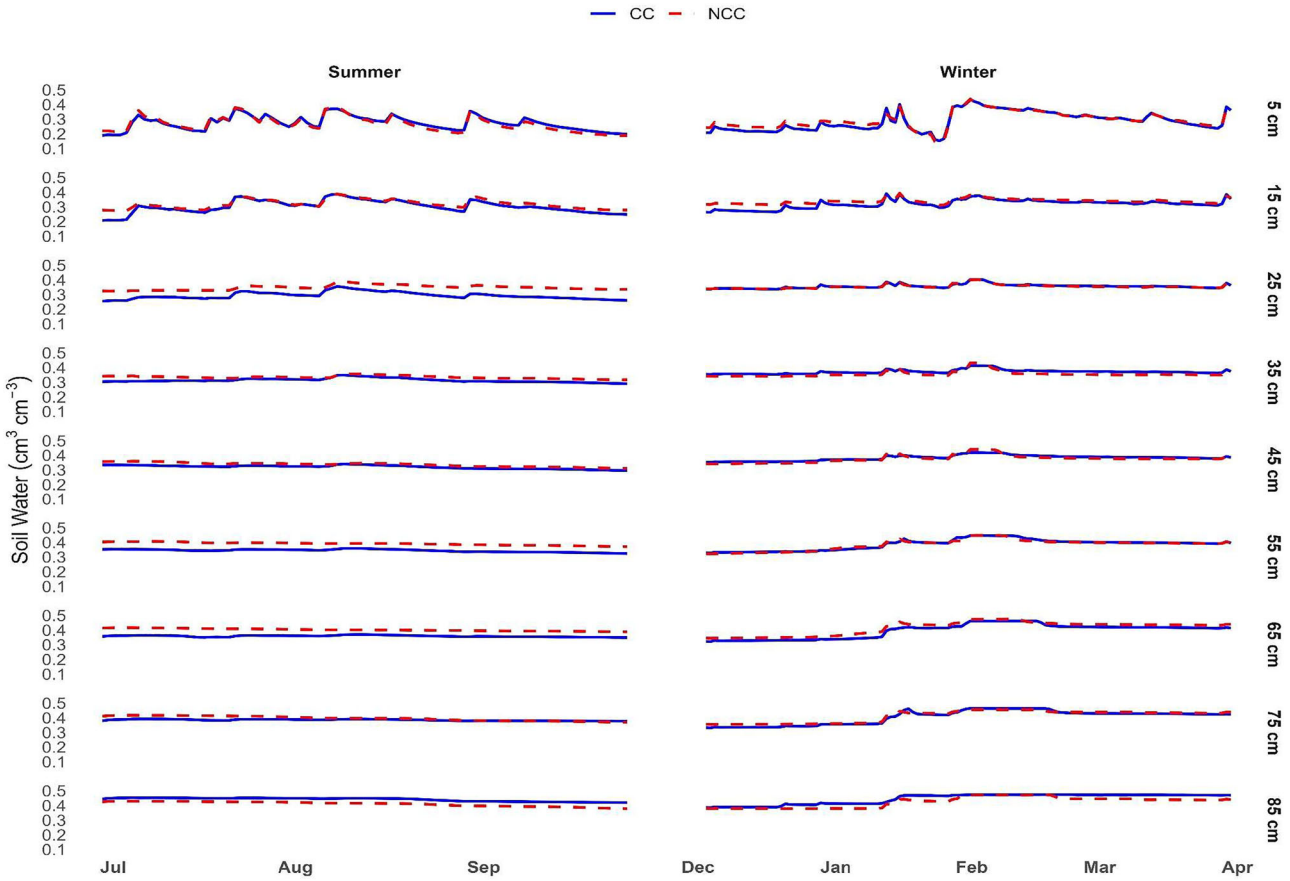


FIGURE 4 Changes in volumetric soil water content at nine soil depths from June 28, 2023, to September 22, 2023, in the left panel and from November 28, 2023 to March 28, 2024, in right panel for with (CC) and without (NCC) cover crop at the Springerton, IL site.

CC soils than for NCC soil within 75- to 80-cm soil depth. Translocation of silt is a common feature of fragipans (Grossman & Carlisle, 1969). Slow degradation of fragipan horizons could be marked by the E/B horizons, which frequently tongue into grayish polygonal zones. These weak layers of the E/B horizon contrast with well-developed parts of the Btx horizon, providing evidence of biotic activities in the form of root channels (Payton, 1993). We hypothesized that ARG root penetration into the fragipan layer facilitated water percolation might initiate the slow degradation of the fragipan layer from the top downward increasing the thickness of the E/B horizon down to approximately 50- to 70-cm depth through destabilization of void walls, degradation of ferri-argillans, and remobilization of clay to form a glossic feature (Payton, 1993).

Introduction of cover crop mixes altered soil water retention characteristics depending on soil depth. Saturated soil water content increased with CC within 0- to 5-cm depth at Springerton and 25- to 30-cm depth at Marion; these increases in saturated water content correspond to statistical ($p < 0.10$) and numerical (Marion) reductions in soil BD. In addition, the Springerton site showed significant reductions in soil water content at PWP at the 0- to 5-cm and 25- to 30-cm depths measured from soil water retention curves, perhaps ultimately increasing the PAW for the 0- to 5-cm depth, although the difference was not significant ($p = 0.10$). Lu et al. (2020) also observed root induced modification of the soil water retention curve, particularly an increase in saturated water content by 13% in fine-textured soils with the addition of vegetation. In a clay pan soil, Çerçioğlu et al. (2019) noted that CC slightly improved soil hydraulics properties (macropores, coarse and fine mesopores, and saturated hydraulic conductivity) within the 0- to 20-cm soil depth, but they concluded that changes may take several years.

However, at Springerton, a reduction in soil water content at SAT, FC, and PWP levels within the 25- to 30-cm depth indicates cover crop roots might clogged the isolated low-density micropores However, PAW content was similar for NCC and CC, indicating that these changes should not cause any plant water stress (Table 1). Absence of similar effect at Marion emphasized that for soils having fragipan layer close to surface like Springerton, soil water retention properties could be affected by cover crop roots. Rearrangement and compression of soil particles, and pore clogging are among the dominant physical processes associated with root expansion to the compact soil horizons (Lu et al., 2020). Roots compact

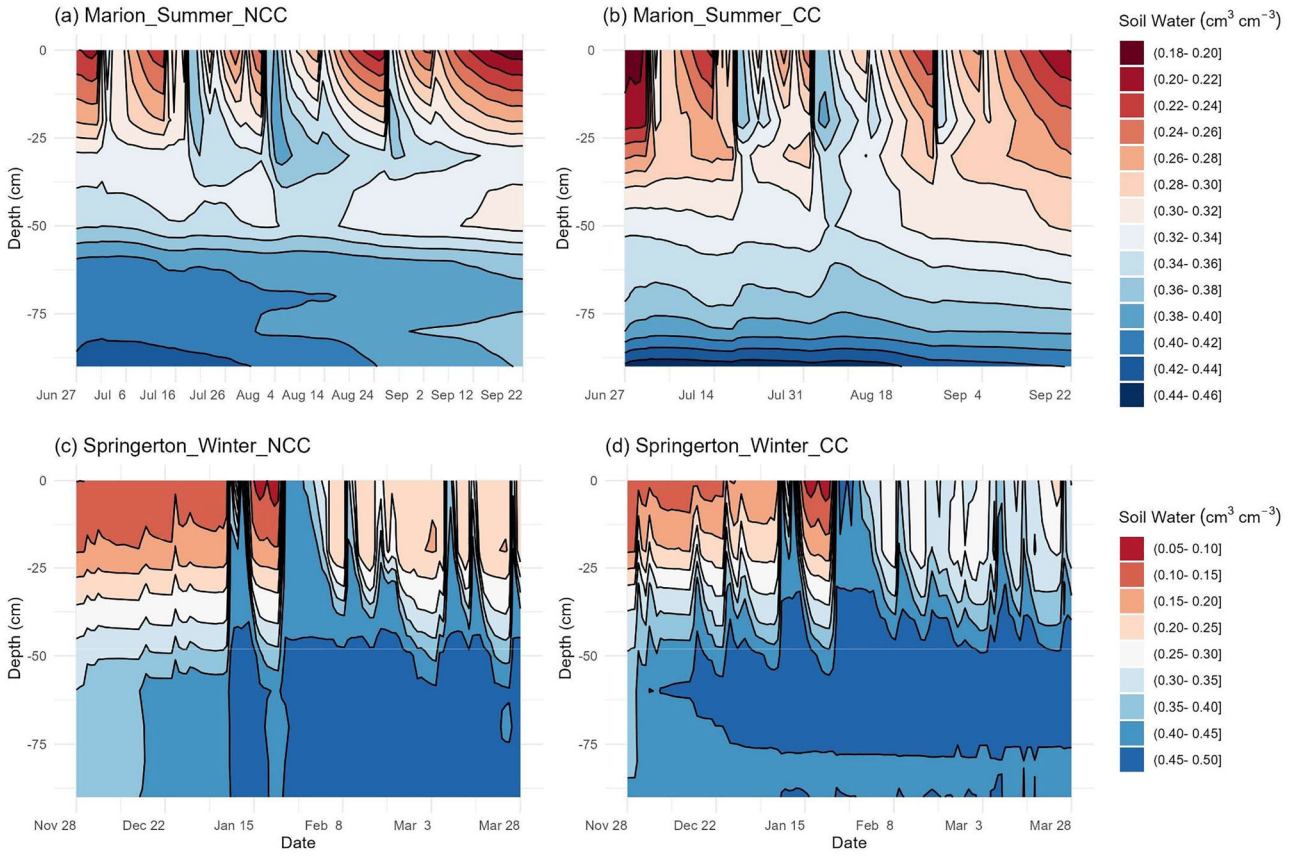


FIGURE 5 Contour plots showing changes in soil water content ($cm^3\ cm^{-3}$) throughout 90-cm depth in response to without (NCC) and with (CC) cover crops during summer at Marion (a and b) and during winter at Springerton (c and d) in southern Illinois.

the surrounding soil if the microporosity is low (Lucas et al., 2019).

Most of the differences in soil water content between CC and NCC occur within the rooting depth (< 55 cm) for both sites (Figure 5). In fragipan soils studied elsewhere, corn and soybean roots at physiological maturity were concentrated in the top 30 cm of soil (Graveel et al., 2002). Rhoton and Römkens (1998) found that plant roots are believed to be restricted to the available water above the fragipan layer (<75-cm depth). Only at Marion, CC had lower soil water content than NCC within 25- and 55-cm soil depths, during the growing season. These observations indicate that corn roots under CC can access water up to 55-cm depth, reducing the perched water table above the fragipan layer starting at 70-cm depth. At Springerton, soil water distribution during summer was not different between CC and NCC. Also, in 2022 during the soybean growing phase, soil water storage did not vary between CC and NCC (Chatterjee et al., 2024). These results emphasized that the influence of CC on soil water during the growing season varies across fragipan soils. We hypothesize that changes in soil water distribution in response to cover crop adoption depend on characteristics of the fragipan profile, such as depth to fragipan and thickness of individual horizons.

The water balance in southern Illinois constitutes a surplus from December through May (Wilson et al., 2010). During this period 54% of the annual precipitation occurs as both rain and snow. On the contrary, summertime (June–July) is characterized as water deficient due to less precipitation than the evapotranspiration demand of the standing crop (Wilson et al., 2010). Numerous studies have demonstrated reductions in soil water availability at time of cash crop sowing due to evapotranspiration by prior cover crops during their growth and coupled with insufficient soil water recharge/accumulation post cover crop termination to compensate for cover crop water use (Garba et al., 2022). Chakraborty et al. (2022) also reported a decline in soil water content under CC to the magnitude of 12%, 17%, and 7% within the 0-to 18-cm soil depth compared to NCC at cash crop planting for three consecutive growing seasons. Higher depletion of soil water under CC could be explained by the possibility that decayed cover crop roots create a preferential flow path, increasing water permeability and corn root expansion to this zone (Williams & Weil, 2004).

During winter, precipitation and snowmelt can lead to a rapid rise in perched water table, with a relatively high lateral saturated conductivity that can result in very flashy hydrologic systems (Calmon et al. 2015; McDaniel et al., 2008). At

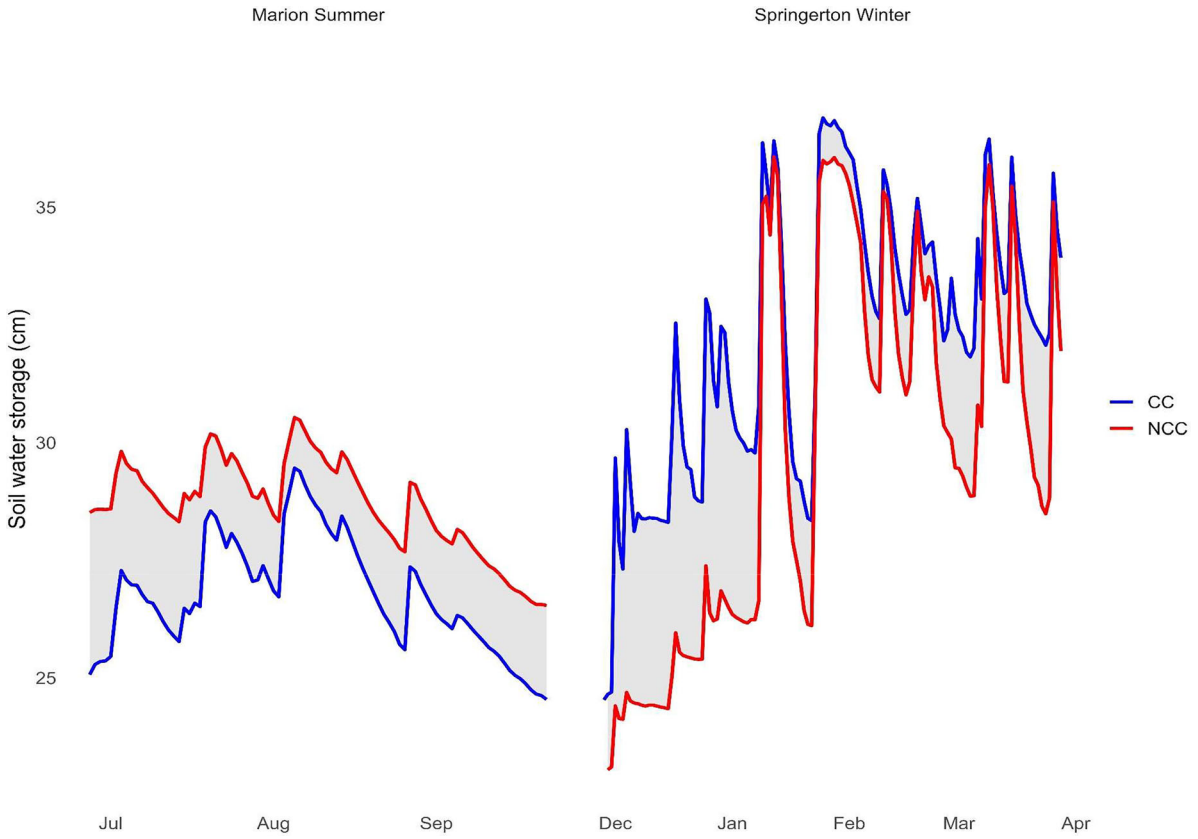


FIGURE 6 Changes in soil water storage (cm) in response to with (CC) and without (NCC) annual ryegrass-based cover cropping during summer (June 27–September 22, 2023) at Marion and winter (November 28, 2023–March 28, 2024) at Springerton, IL.

Springerton, CC had increased soil water storage compared to NCC in winter, but CC did not influence the water balance in Marion. Differences in the level of the water table in between CC and NCC, in winter, depend on the percolation rate and loss of water (evapotranspiration from CC/evaporation from NCC) under the same site (Gile, 1958). Our results indicate that CC under soils with fragipan close to surface could lead to an increase in soil water storage during cover crop growth in winter with low precipitation.

This study demonstrated that inclusion of a multispecies cover crop mixtures in a corn–soybean rotation influenced few physical attributes such as BD, particle size distribution, and water retention characteristics, although effects and magnitude varied between sites. Several limitations should be considered when interpreting these results. First, initial pretreatment soil data were not available, which prevents us from fully ruling out baseline site differences as contributors to the observed outcomes. Nevertheless, the randomized block design, with side-by-side NCC and CC treatments, provides confidence that observed differences largely reflect cover crop management. Second, soil sampling was based on a single core per plot, which may not have fully captured within-plot heterogeneity inherent in fragipan soils. Future studies should employ more intensive soil sampling to better characterize cover crops effect on fragipan horizon and to disentangle the contributions of individual species such as clover, vetch, and ARG.

Differences between Springerton and Marion highlight the role of inherent soil properties in shaping cover crop response. The observed shifts in soil water content under CC also underscore its dual role in soil water dynamics, reducing moisture by lowering perched water table in Marion during summer while simultaneously recharging water in winter as observed in Springerton (Figures 5 and 6). These findings indicate that impacts of CC on soil hydrology are dependent on context, varying with soil type and seasonal precipitation patterns.

5 | SUMMARY AND CONCLUSIONS

Despite major limitations, this study provides novel insights into the role of winter cover crop mixtures in modifying soil physical properties and soil water dynamics under fragipan soils in southern Illinois. The magnitude of changes in soil physical properties probably depended on the length of adoption and the inherent fragipan characteristics at each site, which also influenced seasonal pattern of soil water depletion and discharge. A key strength of this study is that it was

conducted under on-farm conditions and cover crop treatments are well-established (>5 years), providing realistic insights for growers' practice. Nonetheless, observations were limited in spatial scope and depth, highlighting the need for future studies to account for spatiotemporal variability in fragipan characteristics to fully assess the influence of cover crops on soil hydrology across these challenging soils.

AUTHOR CONTRIBUTIONS

A. Chatterjee: Investigation; methodology; visualization; writing—original draft. **E. R. Santiago**: Data curation; formal analysis; investigation; methodology. **D. L. Dinnes**: Data curation; investigation; project administration; resources; writing—review and editing. **D. C. Olk**: Investigation; project administration; resources; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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