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Does no-till cover crop influence *in situ* measured soil water potential and saturated hydraulic conductivity?

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Abstract: Soil water energy determines soil water balance, plant water uptake, and soil thermal properties, but the effects of cover crops (CCs) on *in situ* measured soil water energy and temperature are not well understood. This study investigated how CCs affect *in situ* measured soil water potential (SWP), temperature, and saturated hydraulic conductivity (K_{fs}) during 2 years, with the hypothesis that CC-induced water transpiration can lower SWP. The CCs used included crimson clover (*Trifolium incarnatum* L.), winter wheat (*Triticum aestavum* L.), hairy vetch (*Vicia villosa*), oats (*Avena sativa*), triticale (*Titicale haxaploide* Lart.), barley (*Hordeum vulgare* L.), flax (*Linum usitatissimum* L.), and winter peas (*Lathyrus hirsutus* L.). Soil water potential and temperature sensors were installed at 0–10, 10–20, and 20–30 cm depths. Additionally, K_{fs} was measured *in situ* using a Guelph permeameter. Results showed that actively growing CCs can lower SWP, leading to increased water transpiration from the field compared with no cover crop (NC) management. Also, by lowering soil temperature, CCs can increase evapotranspirational efficiency compared to NC management. Further, by increasing evapotranspirational efficiency, CC, management resulted in increased subsurface water infiltration and storage as shown by higher K_{fs} values compared to NC management. In general, CCs have the potential to reduce SWP and temperature during their growth stages and this can be beneficial to seed germination and microbial activities.

Keywords: precipitation; quasi-steady infiltration rate; soil organic carbon; soil temperature; sorptivity; turgor pressure

Soil water availability and extraction by plants is an important factor at the plant-soil interface, and it also determines crop productivity and environmental sustainability (Salem et al. 2015). Since water retention and movement are energy related (Shukla 2013), soil water balance and budgets are dependent on the water potential operational at the vadose zone. The soil water potential (SWP) is the potential derived from the adhesive, cohesive, adsorptive, osmotic, and gravitational forces between water menisci, ions in the soil solution, soil particles, and gases (Tuller & Or 2005). Therefore, SWP is highly dependent on soil water content, soil pore sizes, soil particles sizes and surface properties of these particles, and the surface tension of soil water (Whalley et al. 2013).

Generally, SWP has a linear relationship with volumetric water content, being zero under saturated conditions and negative as it dries (Or & Wraith 2002). Under field conditions, water content and SWP are dependent on surface characteristics of soil particles. The exchangeable cations and electric double layer influence the presence or absence of presence of water

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films on colloidal surfaces. On sand-sized particle surfaces, SWP results from capillary forces, and is often insignificant (Tuller & Or 2005). Additionally, soil temperature can influence SWP by decreasing the surface tension of water and the contact angle between water and soil particles.

In nature, climate influences soil water content and SWP, directly and indirectly, by moderating temperature, precipitation patterns, wind, humidity, and seasonal variations. Higher atmospheric temperature can result in more soil water evaporation, lower water content and SWP (Aydin et al. 2005). Further, with variation in precipitation (both daily and seasonal), water content and SWP will vary accordingly.

Besides these properties, agricultural management practices can play an important role in SWP and storage. Soil agitation through tillage can alter pore sizes, rearrange soil particles, and influence soil water content, leading to some effects on SWP. For example, Salem et al. (2015) reported significantly higher soil water potential under no-till compared with conventional tillage, suggesting that no-till management can improve water availability and plant water uptake.

The use of cover crops (CCs) in crop rotations has attracted renewed attention as a result of their soil health and crop productivity benefits (Haruna et al. 2020). Under laboratory conditions, various CCs have been reported to lower soil bulk density (BD) (Blanco-Canqui et al. 2011), improve saturated hydraulic conductivity (Drury et al. 2014), and soil water retention (Haruna et al. 2018) compared with no cover crop (NC). Further, CCs have also been reported to increase in situ soil water infiltration rate (Chalise et al. 2019) and cumulative infiltration (Nouri et al. 2019) compared with NC. These studies demonstrate the ability of CC management to improve soil water storage and reduce surface runoff.

Despite the body of knowledge on the effects of CC management on soil water content and availability (e.g., Villamil et al. 2006; Bilek 2007; Abdolahi et al. 2014; Basche et al. 2016; Rorick & Kladivko 2017), there is very limited study on how this practice influences in situ measured SWP. Reasons for limited studies include availability of sensors, sensor accuracy, difficulties with sensor installation and maintenance, environmental and ecological interference, and accessibility. This has limited current understanding of the effects of CCs on plant water uptake. Further, an understanding of the mechanisms involved in soil water availability and uptake when CCs are growing will be useful in water budget analysis during the cash crop growing seasons for CC management. This study is novel because it is one of the first studies to investigate the effects of CCs on the dynamics of soil water energy. Therefore, the objectives of this study included, (1) evaluating the effects of no-till CC on *in situ* subsurface water movement just before their desiccation, and (2) assessing the effects of no-till CCs on *in situ* measured soil water potential. It is hypothesized that, (1) no-till CCs lead to increased subsurface water movement compared with NC management due to increased water transpiration by growing CCs, and (2) increased soil water transpiration by CCs will significantly lower the SWP under CC compared with NC management.

MATERIAL AND METHODS

Site description. This study was conducted in a Cumberland silt loam (fine, mixed, semiactive, thermic, Rhodic Paleudalfs) field located in Murfreesboro, Tennessee, USA (35.816N, –86.373W) (Figure 1). The average elevation of the research site was 190 m above sea level with 0–2% slopes. The soil textural analysis at the site is shown in Table 1. The mean 30-year precipitation and temperature were 1 357 mm and 14.6 °C, respectively. The months of May (139 mm) and October (85 mm) recorded the greatest and lowest precipitation annually. During an average year, the months of January (–3.7 °C) and August (32.3 °C) are the coldest and warmest months, respectively. The ambient temperature and precipitation during the study period is shown in Figure 2.

Management description. The research plots were set up in the fall of 2020 after the cash crop was harvested. Prior to the September of 2020 when the research plots were established, the field was under a 5 year CC management and more than 15 years of no-till. The research plot was set up using a split-split plot design with a completely randomized whole plot with three replicates. The dimensions of each plot was 20.1 m in length by 7.1 m in width. The treatments included two levels of CCs (CC vs NC), with no-till as the type of tillage method. A suite of 8 different CCs were used because of their uniqueness and the diversity of their root densities and morphology. Additionally, this mix of CCs were used because it reflects current trends away from a single species of CCs by producers in various parts of the world (Haruna et al. 2020). These CCs included crimson clover (*Trifolium incarnatum* L.),

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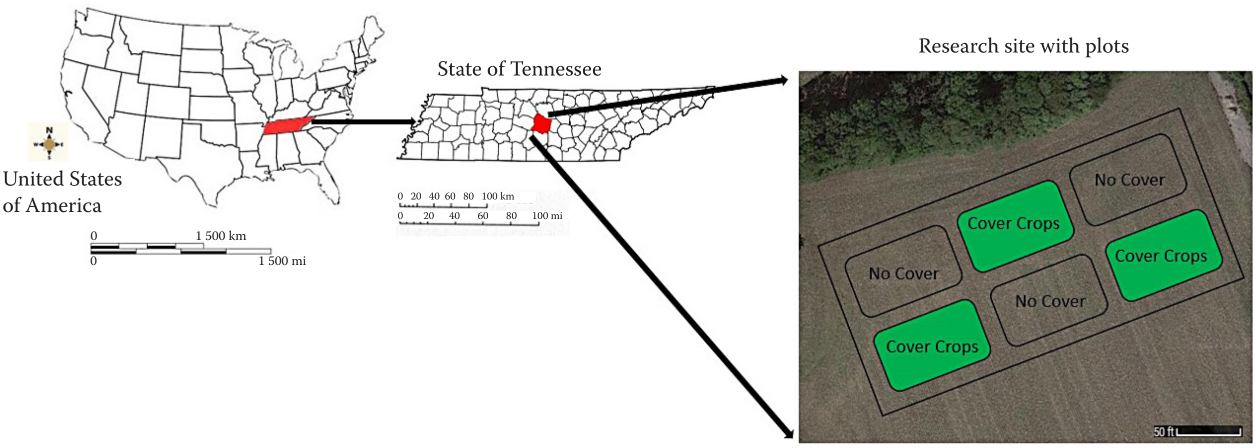

Figure 1. Research site in Tennessee showing research plots (adapted from Haruna et al. 2022a)

winter wheat (*Triticum aestavum* L.), hairy vetch (*Vicia villosa*), oats (*Avena sativa*), triticale (*Titicale haxaploide* Lart.), barley (*Hordeum vulgare* L.), flax (*Linum usitatissimum* L.), and winter peas (*Lathyrus hirsutus* L.). They were planted in October of each year and desiccated in April of the next year using 4.15 kg/ha acid equivalent of glyphosate [N-(phosphonomethyl) glycine]. To complete the desiccation of the CCs, two passes of a 9.1 m CC roller was used a few hours after spraying. Corn (*Zea mays*) (the main cash crop) was planted in April each year and harvested in September. Further information about the research site and management practices can be found in Haruna et al. (2022a).

Sensor installation, saturated hydraulic conductivity measurement, soil sampling and analysis. In situ soil water energy was measured using Watermark® sensors (Model 200SS), a resistive soil moisture tensiometer responsive to soil water potentials greater than –200 kPa. These sensors have been reported to provide accurate results under different wetting and drying cycles for different soil textural classes, including silt loams (Eldredge et al. 1993; Allen 2000; Thomson et al. 2002; Salem et al. 2015). The Watermark® sensors were chosen because their calibration is stable, they have a wide range of measurements (0–200 kPa), and are accurate under different soil conditions (e.g., soil temperature, water content, and salinity). Besides their accuracy, ease of use, and low cost, these sensors were selected because they can be automated for easy data acquisition and wireless data transmission.

Table 1. Particle size distribution as a function of depth for the study site (Cumberland silt loam)

Depth (cm)	Silt	Sand	Clay
		(%)	
0–10	64.17	23.33	12.50
10–20	62.50	21.67	15.83
20–30	60.83	20.83	18.33

The Watermark® sensors were buried in each plot at 0–10, 10–20, and 20–30 cm depths. At each depth, an 8-cm diameter hole was dug to the required depth, filled half-way with a soil sludge and the sensors were then inserted into the soil sludge to ensure good contact between the sensors and wet soil. The sensors were connected to a base node which was powered by solar panels with a battery backup (3 Watermark® sensors and 1 temperature sensor can be connected to 1 base node). The nodes were then wirelessly connected to a cellular gateway for data transmission to the cloud. The sensors were installed on December 3, 2020, and October 31, 2021, and removed on April 8, 2021, and 2022, respectively. These sensors correlate the measured electrical resistance of the soil to the soil water tension.

Soil temperature was measured using an Irrometer® soil temperature sensor (model 200TS) buried at the aforementioned depths in each field. Similarly, they were chosen because of their accuracy and durability. Soil temperature and water potential data was collected every 30 min after installation. Ambient temperature and precipitation were collected from daily averages measured by sensors in the area. All sensors (Watermark®, Irrometer®) were calibrated prior to use by using the method of Shock et al. (1998).

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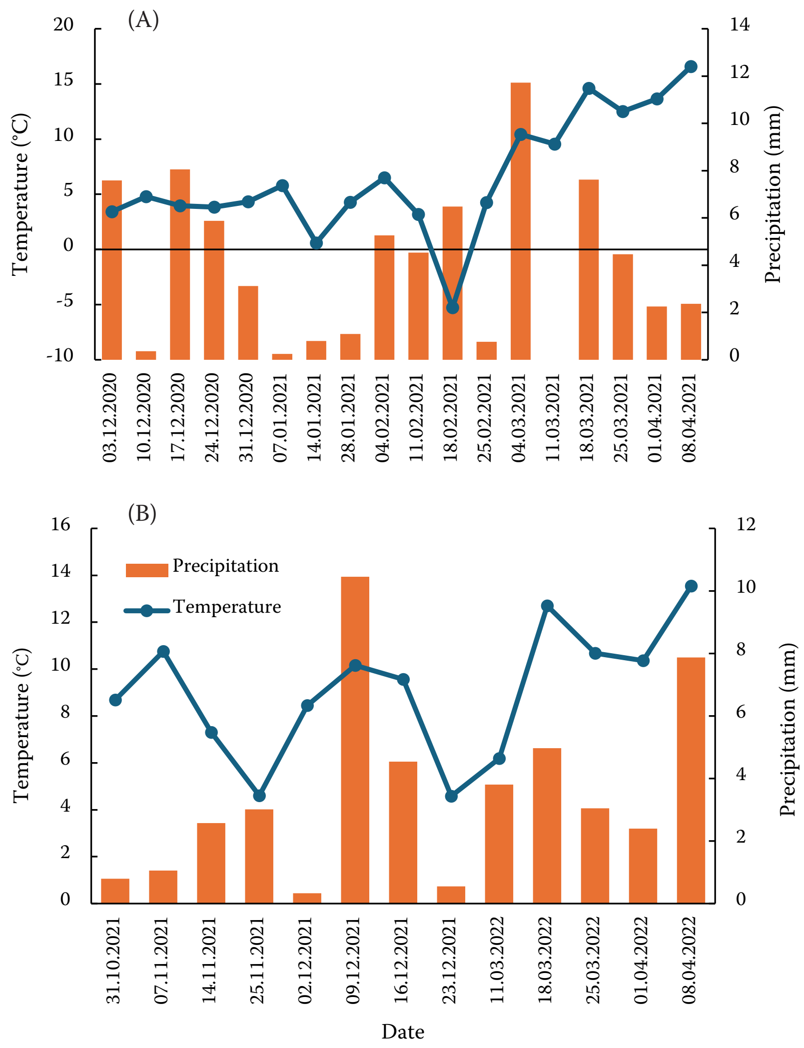

Figure 2. Ambient atmospheric temperature and precipitation at the study site during year 1 (A), and year 2 (B)

In situ subsurface saturated hydraulic conductivity (K_{fs}) was measured using a Guelph permeameter (Humboldt manufacturing company, Elgin, IL, USA) from 10-cm deep holes in each plot just before the CCs were terminated in April of each year. This permeameter measures the three-dimensional water movement from the augured holes into the surrounding unsaturated soil using one or two ponding heads. For this study, two ponding heads were used: 5 and 10 cm. The quasi-steady infiltration rate (*qs*) and sorptivity (*S*) of the soil were calculated from the measured K_{fs} data. The methods of Clothier and Scotter (2002) were used to determine *qs* and *S*. Briefly, *qs* was determined by dividing the steady state (the point during the measurement when the rate of water level change in the Guelph permeameter is constant) (cm/min) by 60 s. This was then converted to mm/h units. The estimates of the K_{fs} and sorptive number (α) were determined using the methods of Reynolds and Elrick (1985) from the ponded head and water discharge data as follows:

$$K_{fs} = \left[(0.0041)\times(R_C)\times(R_2)\right] - \left[(0.0054)\times(R_C)\times(R_1)\right] \quad (1)$$

where:

R_C – a constant for the combined reservoir (for this study, R_C was 35.39 cm^2);

R_1, R_2 – the 5 and 10 cm ponding depths steady flow rate.

The methods of Reynolds and Elrick (1985) were used to determine the matrix flux potential (Φ_m) was calculated as follows:

$$\Phi_m = \left[(0.0572)\times(R_C)\times(R_1)\right] - \left[(0.0237)\times(R_C)\times(R_2)\right] \quad (2)$$

The α parameter was calculated by dividing the K_{fs} by Φ_m.

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The S was calculated using the following relationship:

$$S = \sqrt{(2 \times \Phi_m \times \Delta\theta)} \qquad (3)$$

where:

$\Delta\theta$ – the product of field saturated water content (assumed to be 0.50 cm^3/cm^3) and antecedent soil water content (determined from bulk soil data, cm^3/cm^3) (Clothier & Scotter 2002).

Soil samples were collected using a sampler with a cylindrical core measuring 142.55 cm^3 volume from non-trafficked positions just before CCs were desiccated. They were collected at 0–10, 10–20, and 20–30 cm depths, for a total of 18 soil samples each year (2 treatments × 3 depths × 3 replicates). Any excess soil was trimmed from both ends of the core, each core sealed with a cover and gently placed in plastic bags. They were transported to the laboratory for analysis. Bulk density (BD) was determined using the core method (Grossman & Reinsch 2002). The soil was crushed, passed through a 2-mm sieve and the < 2-mm sized particles were divided into two halves. The first half was used to determine particle size analysis using the pipette method (Gee & Or 2002). The second half was used for soil organic carbon (SOC) determination using the combustion method (Loss-On-Ignition) at 1 200 °C (Schulte & Hopkins 1996).

Statistical analysis. In total, about 118 880 and 96 690 data points were collected during the first and second years, respectively, each for SWP and temperature. The SWP and temperature data were averaged to obtain daily and weekly values. Due to sensor issues, data was not collected during January and February of 2022. A test of normality was conducted on the SOC and BD data using the Anderson-Darling procedure at $P \leq 0.05$ probability level. The data followed a Gaussian distribution. ANOVA was conducted on SOC, BD, SWP, soil temperature, K_{fs}, qs, S using the general linear model in SAS version 9.4 (SAS 2015) for treatment and depth effects. Additionally, interaction effects between treatment and depth was analysed for the SWP and temperature data. Statistical differences were evaluated at $P \leq 0.05$ probability level.

RESULTS

Soil organic carbon and bulk density. Figure 3 shows the effects of CCs and NC management on SOC

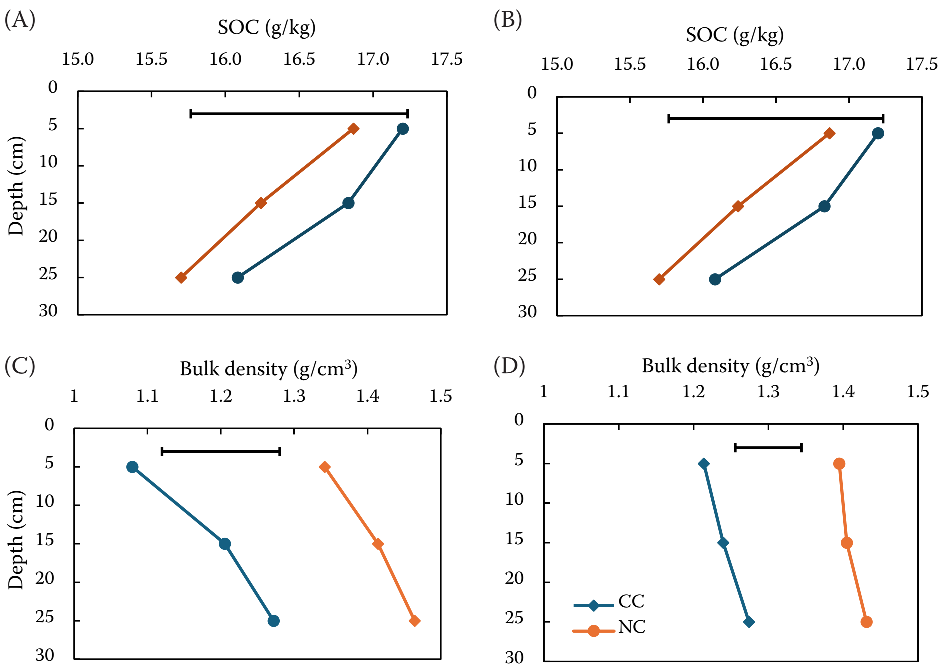

Figure 3. Soil properties with depth during the study period: soil organic carbon (SOC) with depth during year 1 (A), SOC with depth during year 2 (B), soil bulk density with depth during year 1 (C), and soil bulk density with depth during year 2 (D)

Horizontal bars represent the least square differences for all depths at 0.05 probability levels

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Table 2. *In situ* saturated hydraulic conductivity (K_{fs}), and estimated quasi-steady infiltration rate (*qs*) and sorptivity (*S*) at the study site during both years of study

Treatment	*S* (mm/h$^{0.5}$)	*qs*	K_{fs}
		(mm/h)	
Year 1			
CC	13.14[a]	20.83[a]	2.23
NC	5.23[b]	5.00[b]	0.11
ANOVA $P > F$	0.045	0.046	0.158
Year 2			
CC	7.39[a]	17.50[a]	2.31[a]
NC	1.88[b]	0.83[b]	0.06[b]
ANOVA $P > F$	0.046	0.002	0.031

CC – cover crop; NC – no cover crop; means with different letters for a soil property are significantly different at the 0.05 probability level

and BD with increasing soil depth during both years. Even though SOC was not significantly different between both management practices at all depths during both years, it was numerically higher under CC compared with NC at all depths measured (Figure 3A, B). For the CC and NC management practices, SOC decreased with increasing soil depth. Results showed that BD was significantly higher under NC compared with CC during both years and at all depths (Figure 3C, D). Further, BD increased with increasing soil depth during both years.

Sorptivity, quasi-steady infiltration rate, and field-measured saturated hydraulic conductivity. The ANOVA and means for measured soil hydraulic properties are shown in Table 2. During year 1, the *S* and *qs* parameters were 151% and 317% higher under CC compared with NC management, respectively. Although not significant, the K_{fs} was numerically higher under CC compared with NC management. During year 2, the *S*, *qs*, and K_{fs} parameters were 293%, 2 008%, and 3 750% higher under CC management compared with NC management, respectively (Table 2).

***In situ* measured soil water potential.** The means and ANOVA for in situ measured SWP for both management practices during both years are shown in Tables S1 and S2 in Electronic Supplementary Material (ESM). Further, the weekly-averaged SWP values for both years are shown in Figures 4 and 5. Averaged over all depths, SWP was significantly lower under NC compared with CC management during the weeks of 12/3/2020 and 1/14/2021. During the rest of the first year, the depth averaged SWP was significantly higher under NC compared with CC management (except the week of 1/7/2021 where the difference was only numerical). The treatment-averaged SWP was significantly lower at the 0–10 cm depth and increased with increasing soil depth during the first year (Table S1 in ESM). The treatment × depth interaction showed that SWP was higher

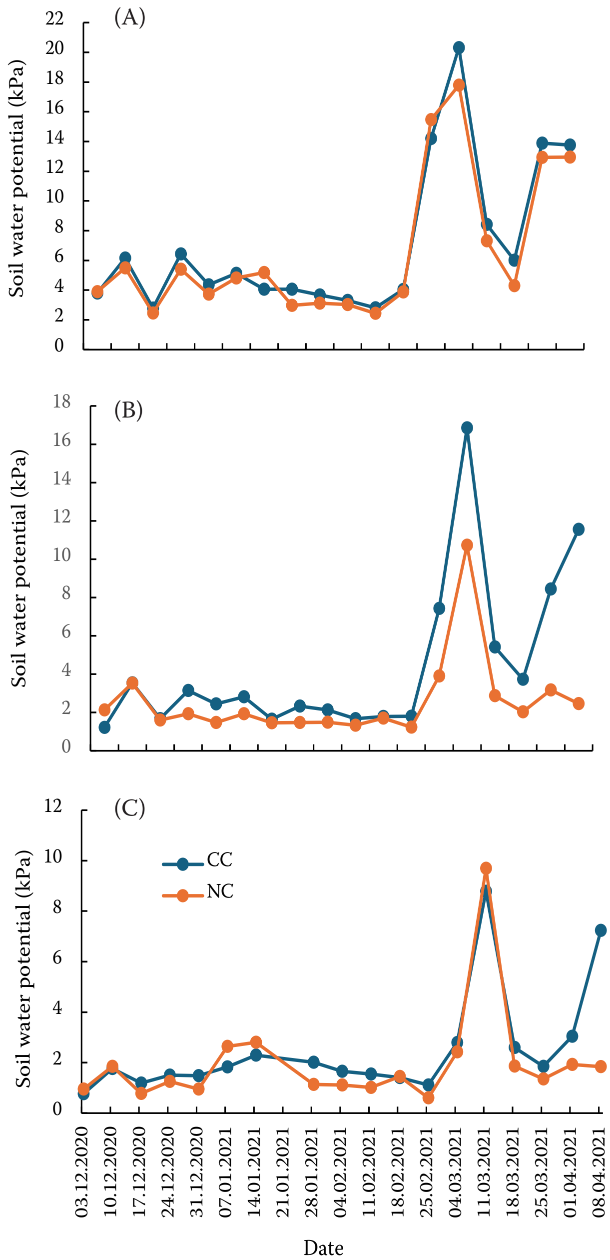

Figure 4. *In situ* measured soil water matric potential at 0–10 cm (A), 10–20 cm (B), and 20–30 cm (C) during year 1

CC – cover crop; NC – no cover crop

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under each management at different depths during the first year (Figure 4). Interestingly, this interaction showed that while SWP was significantly lower under CC management at the 0–10 and 0–20 cm depths, it was significantly lower under NC management at the 20–30 cm depths during the weeks of 3/4/2021 – 3/18/2021. In general, SWP ranged between –15.32 to –1.89 kPa under CC management and between –12.47 to –1.62 kPa under NC management during year 1.

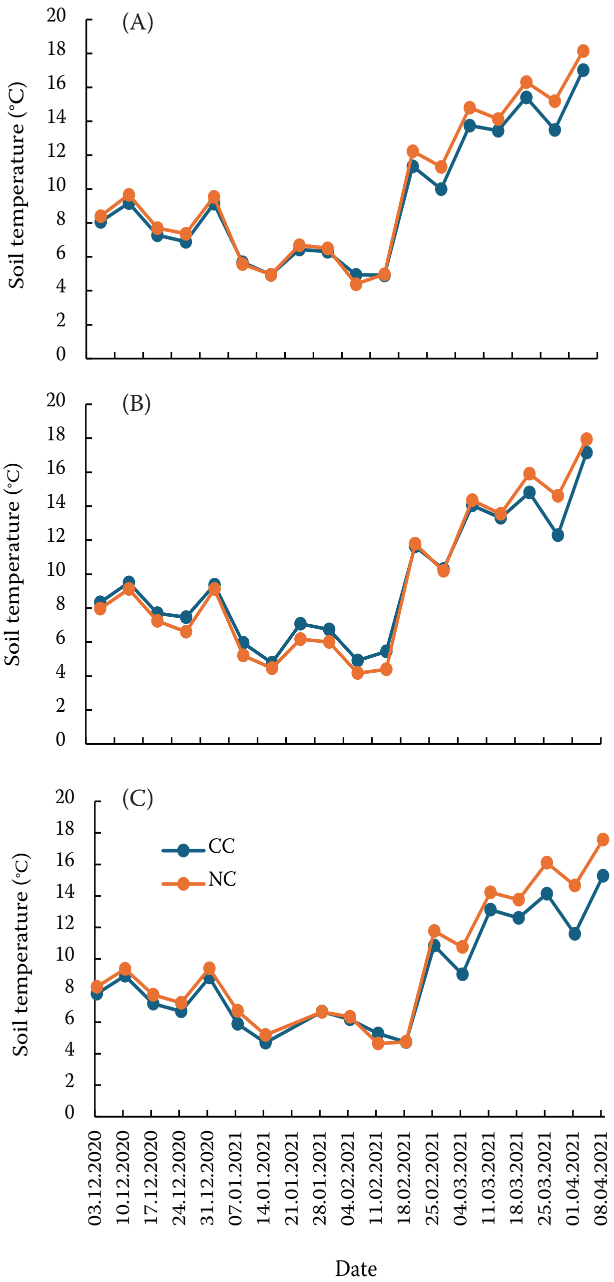

Figure 5. *In situ* measured soil water matric potential at 0–10 cm (A), 10–20 cm (B), and 20–30 cm (C) during year 2

CC – cover crop; NC – no cover crop

During the second year, the depth-averaged SWP was significantly lower under NC management compared with CC management throughout the measurement period, except the weeks of 12/2/2021 and 12/9/2021 (Table S2 in ESM). The treatment × depth interaction followed a similar pattern during year 2 as with year 1, albeit the differences in SWP occurring at different times during the measurement period (Figure 5). Overall, SWP during the second year ranged between –19.54 to –1.67 kPa under CC management, and between –21.44 to –2.21 kPa under NC management.

***In situ* soil temperature**. Tables S3 and S4 in ESM show the means and ANOVA of *in situ* measured soil temperature during both years. Further, Figures 6 and 7 show the average weekly in situ soil temperature at each depth during both years. Results showed that averaged over all depths, soil temperature was higher under NC management compared with CC management during the first month of measurement in year 1. During the second month, CC management had the highest soil temperature compared with NC management. During the final 6 weeks before CC desiccation, CC plots had significantly lower soil temperature. The treatment-averaged soil temperature showed that, on average, soil temperature was higher at the 0–10 cm depth and reduced with an increase in soil depth (Table S3 in ESM). The treatment × depth interaction showed that the soil temperature was similar under NC management at the 0–10 and 20–30 cm depths but was different at the 10–20 cm depth (Figure 6).

At the 0–10 cm depth during the first year, a minimum soil temperature was reached during the week of 2/11/2021 while a maximum was achieved the last measured week of 4/8/2021, with the NC treatment resulting in a higher average soil temperature compared to the CC treatment. Minimum soil temperature occurred at the 10–20 cm depth during the week of 2/4/2021, while the maximum was reached the last week of 4/8/2021 with NC treatment, similarly resulting in an increase in soil temperature compared to CC. At the 20–30 cm depth, the week of 2/11/2021 marked a minimum in soil temperature while the maximum soil temperature occurred during the last week of 4/8/2021 with the higher soil temperature observed in the NC treatment (Figure 6).

During year 2, there was no significant difference in the depth-averaged soil temperature between

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management during the first 3 weeks of measurement. However, during the last week of November and the first week of December, soil temperature was 3% and 7% higher, respectively, under CC compared with NC management. A similar trend was observed during the rest of December and March 2022. However, during the last 3 weeks before CC desiccation, soil temperature was significantly higher under NC compared with CC management. The treatment averaged soil temperature during the second year was similar to the trend during the first year (Table S4 in ESM). The treatment × depth interaction showed that during the first 6 weeks of measurement, soil temperature was higher under CC management at the 10–20 cm depth and higher under NC management at the 20–30 cm depth. During the last 3 weeks before CC desiccation, soil temperature was significantly higher under NC management at the

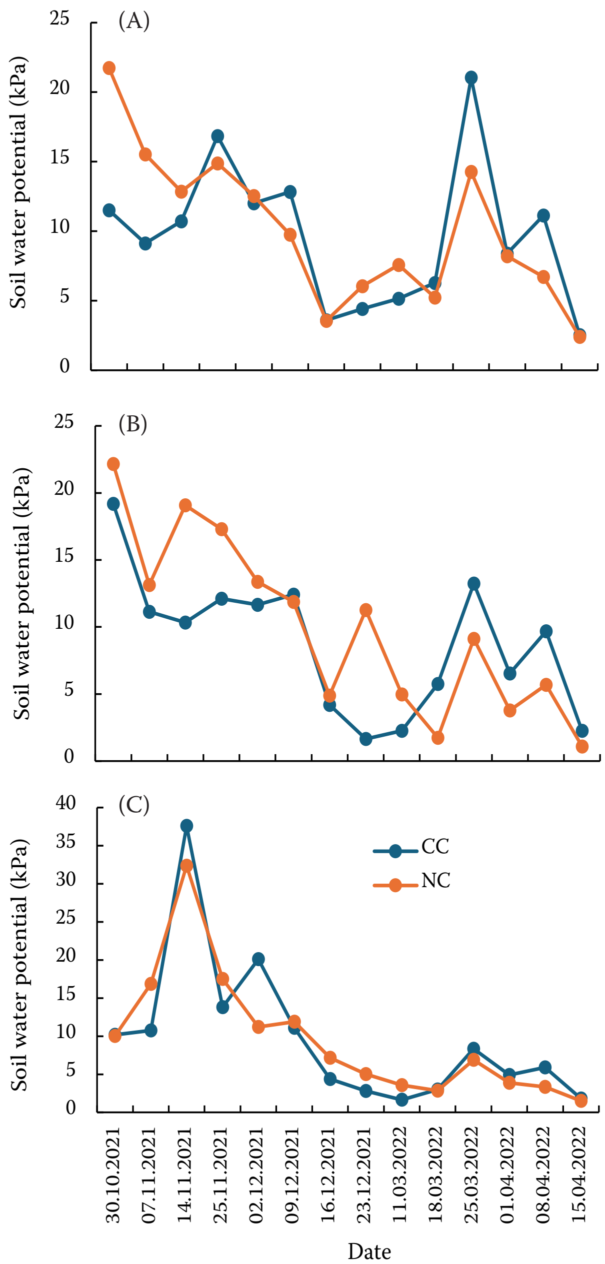

Figure 6. *In situ* soil temperature at 0–10 cm (A), 10–20 cm (B), and 20–30 cm (C) during year 1
CC – cover crop; NC – no cover crop

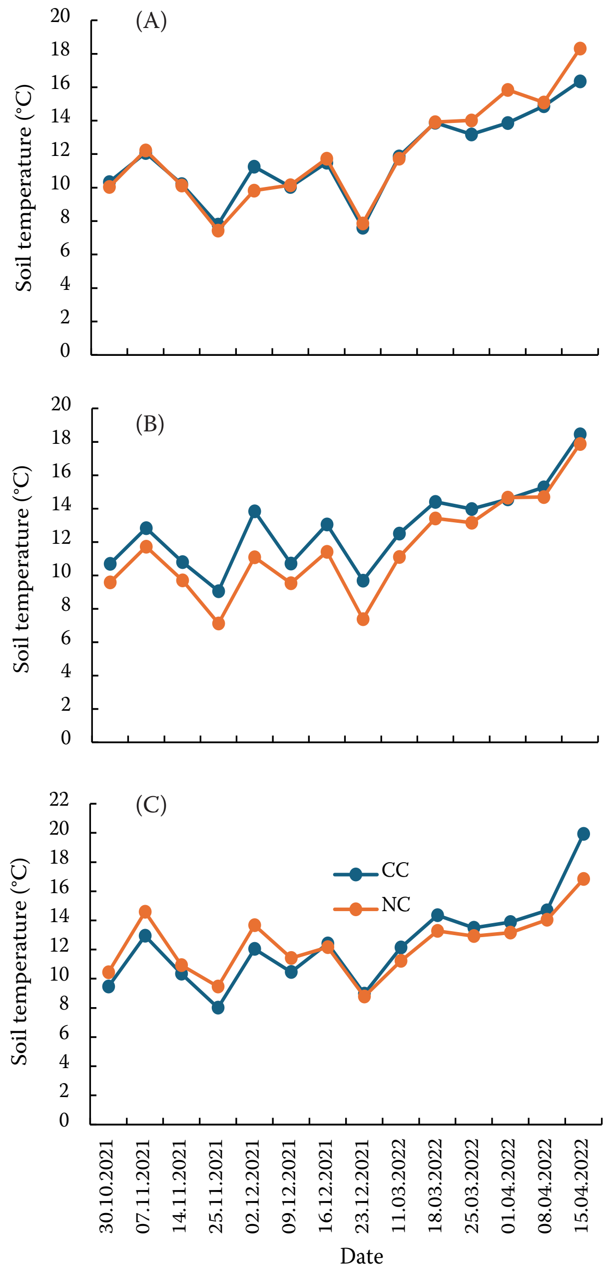

Figure 7. *In situ* soil temperature at 0–10 cm (A), 10–20 cm (B), and 20–30 cm (C) during year 2
CC – cover crop; NC – no cover crop

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0–10 cm depth and higher under CC management at the 20–30 cm depth. In general, during the second year, a minimum occurred at the 0–10 cm depth the week of 11/25/2021, while the maximum was reached the last measured week of 4/15/2022, with the NC treatment showing a higher soil temperature than the CC treatment. At 10–20 cm depth, a minimum was observed the week of 11/25/2021, with a maximum occurring the last week of 4/15/2022, with NC and CC treatments performing similarly. A minimum was achieved at the 20–30 cm depth the week of 11/25/2021 for the CC treatment, and 12/23/2021 for the NC treatment, with maximums, reached the week of 4/15/2022 with the CC treatment, resulting in a higher soil temperature when compared with the NC (Figure 7).

DISCUSSION

Soil organic carbon and bulk density. Cover crops can promote soil C buildup and soil aggregate stability through rhizodeposition and the incorporation of belowground and aboveground biomass (Austin et al. 2017; Haruna et al. 2020). However, the rate of soil C buildup is dependent, among other things, on root architecture and decomposition rates. For example, Mazzoncini et al. (2011) reported that sunflower (*Helianthus annuus*) CC increase SOC accumulation by 16% compared with NC management. Conversely, cereal rye was reported to increase SOC accumulation by 9% (Sainju et al. 2008), and winter wheat was reported to increase SOC buildup by 36% (Haruna 2019), compared with NC management. However, these additions require some time to accrue.

As such, the numerically higher SOC under CC compared with NC management was attributed to different processes like the gradual addition of aboveground CC biomass during the early spring, and significantly after desiccation (Chalise et al. 2019), belowground biomass addition through gradual CC root decomposition, and the various rhizodeposition of the different CCs (Landl et al. 2021). While the aboveground biomass deposition can lead to SOC stratification at the soil surface, especially under no-till management, belowground CC root decomposition can reduce SOC stratification by increasing SOC at slightly deeper depths. The lack of significant differences in SOC between managements may be due to the timing of this study. Since this study was carried out during the first 2 years after plot delineation, enough time have not elapsed for significant enough SOC accumulation under CC management. The reciprocal relationship between SOC and soil depth was attributed to the lower root amount and density with increasing depth as observed during soil sample collection. This phenomenon was also reported by Bodner et al. (2019).

The significantly greater BD values under NC management compared with CC management at all depths measured were attributed to several mechanisms. Since SOC is less dense than soil mineral particles, numerically lower SOC under NC management will generally increase the weight-to-volume ratio compared to CC management (Aşkin & Özdemir 2003; Chaudhari et al. 2013). Additionally, the roots of the CCs can increase total soil porosity (Blanco-Canqui et al. 2011; Chalise et al. 2019) and this has been proven to lower soil BD (Villamil et al. 2006). Further, living CCs and their desiccated residues left on the soil surface can intercept the raindrops. This leads to the dissipation of the kinetic energy of the raindrops (Haruna et al. 2022b), leading to a reduction in soil consolidation and lower BD under CC management compared with NC management. The direct relationship between BD and soil depth was attributed to the weight of the overburden soil, and the lower SOC and root amount and density with increasing soil depth.

Sorptivity, quasi-steady infiltration rate, and field-measured saturated hydraulic conductivity. The initial movement of water into dry soils is governed by the soil matrix capillary potential. As the soil becomes more saturated, the gravitational force takes over and is responsible for water movement. Soil S determines the influence of capillarity on water movement into the soil and, therefore, determines water infiltration at early times and is inversely proportional to antecedent soil water content (Haruna et al. 2022b). The result of the current study shows that CCs can lower BD and soil water content, increase pore size distribution, and increase water infiltration during early times after rainfall or irrigation. Similar results were reported by Blanco-Canqui et al. (2011), and Cercioglu et al. (2018). This can be beneficial in improving the efficiency of irrigation systems, especially in resource-constrained regions of the world.

The qs infiltration rate is the lowest rate at which soil water enters the soil surface (Mbagwu 1997) and is an important hydraulic property that determines irrigation systems selection and water application

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rates. The significantly higher *qs* under CC compared to NC management during both years was attributed to the roots of CCs reducing bulk density, possibly increasing soil porosity and pore connectivity (Villamil et al. 2006). Also, CCs have been demonstrated to reduce antecedent soil water content through transpiration (Haruna et al. 2022b) and this may have caused the higher *qs* infiltration rate under CC management. By increasing the *qs* infiltration rate, CCs can increase soil water storage and decrease surface water ponding and runoff on flat and slopping surfaces, respectively, compared with NC management. This can be beneficial for agronomic and environmental purposes. However, it is also important to note that CC transpiration can deplete the soil of water, and this can be detrimental to subsequent cash crop productivity, especially in arid-semi-arid environments.

The Guelph permeameter-measured K_{fs} demonstrates the influence of gravitational forces on water infiltration, and it determines subsurface water movement and storage. Therefore, for a given rate of water application, the current study shows that CC management can lower the water content behind the wetting front compared to NC management. This can be attributed to the proportion of larger pores in the subsoil. In an earlier study at the same study site, Haruna et al. (2022a) reported that CCs improved macroporosity (> 1 000 μm effective diameter) and mesoporosity (60–1 000 μm effective diameter), which results in water drainage under gravity. Carof et al. (2007) and Abdollahi et al. (2014) reported similar findings. Therefore, the wetting front will move deeper into the soil under CC management in order to accommodate the cumulative change in water storage. The resulting effect is deeper groundwater recharge. This confirmed the first hypothesis.

***In situ* measured soil water potential.** Soil water potential is the amount of work that must be done per unit quantity of pure water to transport an infinitesimal quantity of water reversibly and isothermally from a reference pool to a point under consideration (Aslyng 1963) and is an important measure of the activity of water in the soil. The significantly lower SWP under CC compared with NC management during the month of December (year 1) was attributed to the activities of emerging CCs which were planted in October. In order to grow and develop, plants need to maintain turgor pressure by keeping a lower internal potential than the SWP (Arikan et al. 2021). Due to the high amount of precipitation during this period (Figure 2), the emerging CCs need to transpire water in order to maintain their cell turgor pressure. As a result, a pressure differential is created between the cell and soil, which will result in water movement from the soil into the plant cells (absorption of water). As the cycle continues, eventually, the SWP will be lowered compared to plots without active plants. This confirmed the second hypothesis.

As the soil temperature reduces during succeeding weeks, these CCs become dormant and transpiration reduces, leading to an increase in SWP under CC compared with NC plots. As the soil temperature gradually increases over the last 2 months before desiccation, transpiration increases again, thus leading to lower SWP under CC management compared with NC management. Also, the significant treatment × depth interaction noticed during year 1 (weeks of 3/4/2021–3/18/2021, Figure 4) was probably due to the higher precipitation received during the week of 3/4/2021 (Figure 2A). Higher transpiration reduces antecedent soil water content, and this can increase water storage after precipitation (Haruna et al. 2022b), especially at the rooting depth. Therefore, this may have led to the lower SWP under CC compared with NC management at the top 2 measured soil depths (Figure 4). This leads to an increase in vegetative growth of the CCs, reduced soil bulk density (Figure 3C), increased biomass production, and increased residue return to the soil as noted in the slightly higher SOC under CC management (Figure 3D). Consequently, the lowering of SWP under CC management before desiccation may have resulted in significantly higher *S*, *qs*, and K_{fs} compared with NC management. Results of the current study also demonstrate that water transpiration requires more energy than water evaporation during the spring season due to the higher SWP under CC compared with NC management. Therefore, the inclusion of CCs into crop rotation cycles can influence the soil water energy partitioning at the soil-plant-atmosphere continuum, leading to better water use efficiency during the spring season.

This phenomenon was similar during the second year. However, earlier sensor installation during the second year showed that SWP was significantly higher under CC compared with NC management during November. This was attributed to the CC residues from year 1 (which takes more than 7 months to totally decompose; Haruna et al. 2022b) which were still visible during sensor installation. These residues can reduce surface water evaporation, thus lowering SWP compared with NC management.

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Results of the current study demonstrate that CCs can transpire excessive water out of the soil during the majority of their vegetative lifecycle. While this phenomenon can be beneficial for water infiltration and for lengthening the growing season in humid and subhumid environments, it might be detrimental in arid and semi-arid environments. Further, if the CCs are not terminated in a timely manner, they can significantly lower SWP and reduce the growth and development of the succeeding cash crop. This is especially true for practices where the cash crops are planted while the CCs are still growing.

During the first year, the lowest SWP for all depths occurred during the week of 2/18/2021, which corresponds to a week of relatively high precipitation and below-freezing temperatures. During the last three weeks before desiccation in 2021, SWP was significantly lower under CCs compared with NC management at the 10–20 and 20–30 cm depths, corresponding to root activity. Further, results showed that lower bulk density and higher SOC can lead to lower SWP.

***In situ* measured soil temperature**. Soil temperature is important for microbial activity, seed germination, and water and nutrient movement within the vadose zone. For example, Qiu et al. (2005) reported a linear relationship between soil temperature and microbial activity and abundance. Further, Song et al. (2013) reported that corn germination and yield are directly related to soil temperature.

Results of this study showed that soil temperature generally followed ambient temperature trends, however, there were some significant effects of treatment. Generally, during both years, soil temperature was significantly lower under CC management compared with NC management (when averaged over all depths), specifically when the temperature begins to increase throughout the spring season (Tables S3 and S4 in ESM). Further, soil maximum temperature and daily temperature amplitude were increased under NC management compared with CC management. These were attributed to the living CCs and their residues reducing the amount of solar radiation reaching the soil surface. Further, this lower soil temperature could be as a result of the slightly higher SOC under CC management. Soil organic carbon has been reported to increase the volumetric heat capacity of the soil (Haruna et al. 2017; Zaibon et al. 2019; Haruna & Anderson 2022; Haruna et al. 2023). Therefore, higher SOC can increase the ability of the soil to buffer against rapid heat transport, thereby keeping the soil temperature more stable over a longer period. Consequently, CC management can maintain soil temperature for short periods of time, and this can positively benefit microbial activity, seed germination, root growth and development, and water and nutrient transport. In a rapidly changing global climate, current results also show that CCs can better buffer against rapid soil temperature change (Haruna & Anderson 2022).

Soil temperature was inversely related to SWP during both years. Generally, higher atmospheric temperature results in higher evapotranspiration rates, and this probably led to the lower SWP noticed under higher soil temperatures. Lavigne et al. (2004) reported similar findings.

The current study demonstrated the effects of CCs on soil hydraulic properties and water potential, not just prior to their desiccation, but during their entire lifecycle and will improve current understanding of how CCs influence water availability and transport in situ. However, the limitation of this study is that it was conducted during the CC growing season. Future studies should monitor SWP after CC termination and during the cash crop growing season and collect soil samples year-round to evaluate the seasonal changes between management groups. This will help bridge the gap between what happens after CC termination and during the cash crop growing season with respect to SWP and in situ soil hydraulic properties.

CONCLUSION

This study evaluated the effects of CCs on *in situ* measured soil hydraulic properties and water potential in a rainfed system. Results showed that, prior to going dormant during the early fall period, CCs maintained their turgor pressure by transpiring water out of the field, leading to lower soil water pressure under CC compared with NC management. Lower soil temperatures during winter months lead to CCs going dormant, reducing water transpiration and increasing soil water potential relative to NC management. About 2 months prior to CC desiccation, higher soil temperatures led to higher transpiration rates, lower soil water potentials, improved sorptivity, quasi-steady infiltration rate, and saturated hydraulic conductivity, compared with NC management. This can lead to increased water infiltration and storage under CC management. However, if not terminated appropriately and in a timely manner, CCs may reduce

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the moisture available for the subsequent commodity crop, especially in arid and semi-arid environments. Therefore, this study showed the benefits of CCs on *in situ* measured hydraulic properties and water potential and also highlighted the need for proper management in order to achieve these benefits. Based on current results, the implications for future studies include the evaluation of the coupled effects of tillage and CCs on *in situ* measured soil water potential.

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