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# Do Cover Crops Influence In Situ Soil Water Potential After Termination?

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**Abstract:** Soil water movement is energy-dependent and is influenced by various management practices. It can be understood by measuring the soil water potential (SWP); however, the influence of cover crops (CCs) on SWP is not currently well understood. The objective of this study was to assess the effects of CCs on SWP before and after termination in order to understand their effects on soil water availability for the subsequent cash crop. The experimental design was a completely randomized design with two levels of CCs (CCs vs. no cover crop [NC]) with three replicates. The SWP sensors were buried at 0–10, 10–20, and 20–30 cm depths before CCs were planted. Additionally, soil samples were collected at the aforementioned depths just before CC termination for soil organic carbon (SOC), bulk density (BD), and saturated hydraulic conductivity ($K_{sat}$) analysis. Results showed that CCs increased SOC and $K_{sat}$, and significantly lowered BD compared with NC management. Before termination, CC plots had significantly lower SWP values compared with NC management, suggesting that the transpirational needs of the CCs can lead to lower water content. After termination, CC management also resulted in lower SWP, suggesting that CCs can increase water-use efficiency by improving soil health parameters. However, effective planning is required for CC implementation, especially in semiarid and arid regions.

**Keywords:** bulk density; saturated hydraulic conductivity; soil organic carbon; soil water content

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## 1. Introduction

Although the most important factor in crop production is water, its availability and movement are energy-dependent. Processes like water and solute movement, plant water extraction, surface water evaporation, deep drainage, and water transpiration by plants are reliant on soil water potential (SWP) [1]. The SWP is the amount of work, per unit quantity of pure water, needed to move an infinitesimal quantity of water isothermally and reversibly to a point under consideration from a reference pool [2]. Therefore, SWP arises from the interactions of surface tension, adsorption, and gravitational and osmotic forces among water menisci, ions in the soil solution, soil particles, and gases [3]. The SWP is very important because it is a direct indicator of water availability for plants and soil organisms. As such, SWP is more important than soil water content, because it (SWP) depicts the readily extractable water from the soil, and this is crucial for understanding plant stress levels and for irrigation management.

During the crop growing season, plant water stress can occur at various stages of development, and this can influence irrigation timing and the overall water budget. For example, ref. [4] reported that water stress during the early growth stages of corn (*Zea mays*) significantly decreased the plant dry weight. Conversely, ref. [5] reported that the greatest water stress occurred for corn during the bracketing flowering stage. While there is still no consensus on the timing of water stress, there is a consensus that water stress significantly reduces crop growth and productivity [6–8]. Since water stress is determined by understanding soil water energy, it is important to identify soil properties and management practices that influence SWP.

Soil water potential is influenced by soil water content, particle size distribution (particularly the clay-sized soil particles), and soil management practices. Generally, the volumetric water content of soils is proportional to SWP, with drier soils having lower SWP (more negative) [9]. The electrical double layer, exchangeable cations, and capillarity influence the presence of water films on the surface of clay-sized particles. On sand-sized particles, capillarity influences SWP and is mostly insignificant [2].

Various land management practices have been reported to influence SWP. In a study on a Vertic Luvisol in Spain, ref. [1] reported that no-till management significantly increased SWP compared with conventional tillage (moldboard plow, 30 cm below the soil surface), minimum tillage (chisel plow, 20 cm below the soil surface), and reservoir tillage. This was attributed to a decrease in water evaporation caused by surface residue in the no-till management. Conversely, ref. [10] reported that ditch-buried straw return (DB-SR) tillage significantly reduced SWP compared to no-till in a sandy loam gleyi-stagnic anthrosol in China. The authors [10] attributed this to the higher soil organic carbon (SOC) under the DB-SR management due to several years of straw incorporation. This SOC significantly retained more soil moisture, leading to lower SWP [10].

Inclusion of cover crops (CCs) in crop rotation cycles has environmental and agronomic benefits by providing protective vegetative cover during a fallow period, recycling excess nutrients at the end of the growing season, and atmospheric nitrogen fixation [11,12]. Researchers have reported conflicting results on the effects of CCs on soil water content and retention. For example, refs. [13,14] reported significantly higher soil water content under CC management at the 0–10 cm soil depth in long-term studies compared with no cover crop (NC) management. In contrast, ref. [15] showed that soil water content was significantly lower under CC compared with NC management as a result of increased water transpiration. Further, ref. [16] reported that cereal rye (*Secale cereale*) significantly increased laboratory-measured soil water content at −10 and −30 kPa water pressures by 4 and 5%, respectively, compared with NC management. Conversely, ref. [17], utilizing the same CCs and at the same depths, reported no significant differences in laboratory-measured water content at these pressures.

Notwithstanding the availability of studies on the influence of CCs on soil water content and availability [18–21], there are very limited studies on in situ-measured SWP as influenced by cover crops. With the increase in the adoption of CCs, there is a need to understand their effects on soil water energy dynamics, not just before termination, but also during the commodity crop growing season. Therefore, the objective of this study was to evaluate the effects of CCs on SWP during their vegetative period and after termination. As highlighted above, while CCs can transpire water from the field (resulting in lower SWP), this can reduce the water content behind the wetting front, thereby leading to a potentially higher saturated hydraulic conductivity (potentially increasing SWP). For fields located in similar climatic conditions to those of the present study, early spring precipitation can blunt any effects of CCs on SWP. Therefore, it is hypothesized that SWP values will be similar between management practices post-termination.

## 2. Materials and Methods

### *2.1. Site Description*

The study site was located in Estill Springs, Tennessee, USA (35.330 N, −86.012 W, 310 m asl), with <2% slopes. Table 1 shows the soil textural characterization relative to soil depth of the USDA-classified Holston sandy loam (fine-loamy, siliceous, semiactive, thermic Typic Paleudults) soil at this location. The mean 4-decade precipitation and temperature were 1422 mm and 15 °C, respectively. The months of December (122 mm) and August (51 mm) recorded the highest and lowest precipitation annually. Over the preceding 4 decades, the months of January (−1 °C) and July (31 °C) were the coldest and warmest months annually. The atmospheric conditions at the site during the period of this study are presented in Figure 1.

**Table 1.** Soil textural distribution relative to soil depth at the research site.

| | Clay | Silt | Sand |
|---|---|---|---|
| Depth (cm) | | ---------------------------------------%----------------------------------------- | |
| 0–10 | 14.2 | 22.5 | 63.3 |
| 10–20 | 16.7 | 21.7 | 61.7 |
| 20–30 | 15.8 | 20.8 | 63.3 |

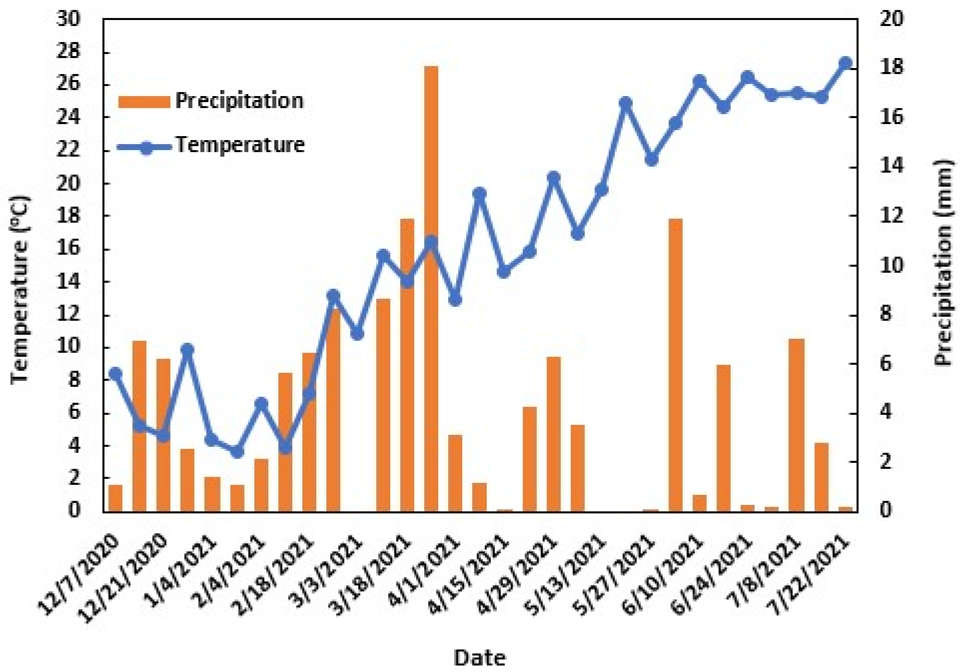


**Figure 1.** Ambient atmospheric temperature and precipitation at the research site. All dates are in the MM/DD/YYYY format.

*2.2. Management Description*

The plots used for this research were delineated in September of 2020 after harvest of the cash crop. Preceding the establishment of the research plots during the Fall of 2020, the field had seen 2 decades of CC management and over 2.5 decades of no-till. The experimental design of the study was a completely randomized design using two levels of CCs (CCs vs. NC) and three replicates each. All plots were under no-till management for this study. The dimensions of each plot were 20.1 m (length) $\times$ 7.4 m (width). A 6-way CC mix was chosen for its unique characteristics and the diversity of root densities and morphologies, reflecting current trends among producers in this region moving away from single-species CC. The mix included winter wheat (*Triticum aestivum* L.), crimson clover (*Trifolium incarnatum* L.), triticale (*Triticale hexaploide* Lart), hairy vetch (*Vicia villosa*), oats (*Avena sativa*), and cereal rye (*Secale cereale* L.), which were planted in October 2020 and terminated in April 2021 using 4.15 kg ha$^{-1}$ acid equivalent of glyphosate [N-(phosphonomethyl) glycine]. To complete the termination of the CCs, two passes of a 9.1 m CC roller were made a few hours after spraying. Corn (*Zea mays*) (the primary cash crop) was planted in April 2021 and harvested in September of the same year. Extensive details about the study site and management are available in [22].

*2.3. Sensor Installation, Soil Sampling, and Analysis*

In situ soil water energy was measured using Watermark® sensors, model 200SS (Irrometer Company Inc., Riverside, CA, USA), a soil water tensiometer (resistive) responsive to SWP higher than −200 kPa. Previous researchers [1,23–25] have demonstrated that these sensors provide accurate results under varying drying and wetting regimes for most soil types. These sensors were chosen due to their range of measurement, stable calibration, and accuracy under diverse soil conditions, and because of their ease of automation for real-time data acquisition and transmission. These sensors link the measured electrical resistance of the soil to the soil water tension. For the sandy loam soils at this site, the field capacity corresponds to between −20 and −30 kPa SWP, and permanent wilting points correspond to −1500 kPa SWP [22]. Due to the rainfall amount, and shade from nearby tree-line and growing cash crops, the sensors provided accurate readings for the field during the majority study period. As such, the study did not extend past the month of July.

The sensors were installed in each plot at 3 depths: 0–10, 10–20, and 20–30 cm. A hole was dug (6 cm diameter) at each depth, half filled with a soil slurry, and the sensors were then inserted into the slurry to maintain good contact between the sensors and wet soil. The sensors were installed in non-trafficked interrow positions in each plot. The sensors were connected to a base node powered by solar panels with a battery backup (3 Watermark® sensors and 1 temperature sensor can be connected to 1 base node). A cellular gateway, linked to the nodes wirelessly, was used for data transmission and storage. The sensors were installed on 30 November 2020. On 20 April 2021, the sensors were removed from the field to allow for the termination of the CCs and the planting of the cash crop. The sensors were re-installed about 3 h later in newly dug holes, approximately 0.6 m from the previous holes. Before sensors were re-installed, their accuracy was determined. Inaccurate sensors were replaced by another pre-calibrated sensor. Calibration was done using the Watermark sensors, tensiometers, and thermistor using the method of [26].

A 143 $cm^3$ cylindrical core was used to collect soil samples from non-trafficked interrow positions, prior to CC termination. They were collected at 10 cm intervals from the surface down to 30 cm, for a total of 18 soil samples (2 treatments × 3 depths × 3 replicates). Surplus soil was cut from the ends of the core using a soil spatula; each core was covered, placed gently in plastic bags, and then transported to the laboratory for analysis.

During analysis, the cover was removed from the soil cores, and a cheese cloth was placed at the bottom using rubber bands. The samples were then saturated from the bottom in a tub (the water had an electrical conductivity of 0.3 dS $m^{-1}$ at 25 °C) for at least 24 h. After saturation, the saturated hydraulic conductivity ($K_{sat}$) was determined using the constant head method. For flows < 0.1 cm $hr^{-1}$, the falling head method was used [27]. The soil was then dried in an oven at 105 °C until equilibration, and bulk density (BD) was determined using the core method [28]. After crushing and sieving (using a 2 mm sieve), the <2 mm-sized particles were divided into two equal parts. The first half was used for soil textural analysis using the pipette method [29]. The second half was used for soil organic carbon (SOC) determination in a Skalar® SNC analyzer (Skalar Analytical B.V., Breda, The Netherlands). This analyzer uses dry combustion (in a furnace) to cause the C to be completely oxidized to $CO_2$ (at 1200 °C) [30], which is then measured by infrared detection.

*2.4. Statistical Analysis*

In total, about 191,080 data points were collected for SWP. The SWP data were averaged to obtain daily and weekly values. Further, the few datasets outside the range of measurement of the sensor (indicated as ‘0′ in the dataset) were omitted from the final analysis for this study. A test of normality was conducted on the SOC and BD data using the Anderson–Darling procedure, with results showing a normal distribution. ANOVA was conducted on SOC, BD, SWP, and soil temperature using the general linear model in SAS version 9.4 [31] for treatment and depth effects. Additionally, interaction effects between treatment and depth were analyzed for the SWP data. Statistical differences were analyzed at a probability level of $p \leq 0.05$.

## 3. Results and Discussions

### *3.1. Soil Organic Carbon, Bulk Density, and Saturated Hydraulic Conductivity*

Figure 2 shows the SOC, BD, and $K_{sat}$ relative to soil depth measured just before CC termination. Results show no significant differences in SOC between treatments, although SOC was slightly greater (not significant) under CC compared with NC management at all sampled depths (Figure 2a). The lack of significant differences in SOC between treatments was attributed to the timing of the study. Since this was the first year of study and the field was under CCs prior to research establishment, there might not have been enough time for the CC residues added during this study to have totally decomposed. As such, the numbers were similar between the two management practices. The numerical differences can be attributed to two mechanisms. First, the gradual addition of aboveground residues from the CCs and the slow decomposition of some of the belowground residues during the first year may have added some SOC to the CC plots. Second, due to the lack of residue addition under the NC management, the gradual breakdown of previously accumulated SOC by soil microorganisms can lead to a slight depletion of SOC, further increasing the numerical difference in SOC between the management practices. A similar trend, with significant differences in SOC between CC and NC, was reported by [32]. This numerically greater SOC may be important for aggregate formation and strengthening, and increased water and nutrient retention. As expected, SOC decreased with an increase in soil depth, probably due to fewer plant roots and plant residues and less microbial activity and density with increasing soil depth.

The current study found a significantly higher BD under NC compared with CC management at all depths sampled (Figure 2b). Active plant roots have been reported to increase soil porosity, leading to lower BD values [33]. As such, the absence of living roots in the NC plot is thought to have led to higher BD values under this management compared with CC management. Another reason for the greater BD values under NC management may be the lower SOC under this management. The lower density of SOC means that management practices with higher SOC will have a lower weight-to-volume ratio, as noticed under CC management. Finally, since plant leaves and residues can intercept and dissipate the kinetic energy of raindrops [32], CC biomass can reduce soil consolidation, resulting in lower BD under this management. Results also showed that BD significantly increased with increased soil depth. This was attributed to a reduction in SOC with an increased depth from the soil surface (Figure 2a) and the weight of the overburden soil.

Soil BD can influence water movement and storage [34]. The maximum liquid flux through the soil is measured by the $K_{sat}$. Current results showed that CC management significantly increased $K_{sat}$ values compared with NC management (Figure 2c). This was attributed to (1) slightly higher SOC, (2) lower BD, (3) CC roots, and (4) higher CC biomass which reduces raindrop energy and the resultant soil compaction under CC management. Higher SOC has been demonstrated to increase soil aggregation [35] and macro- (>1000 μm effective diameter) and mesoporosity (60–1000 μm effective diameter) [36]. Since maximum flow rate is facilitated by non-capillary pores [37], these may have resulted in greater $K_{sat}$ values under CC as opposed to NC management. Further, plant roots can increase soil porosity and the connectivity of these pores. Additionally, CCs can transpire excessive water from the soil, leading to lower water content behind the wetting front under CC compared with NC management. This, therefore, moves the wetting front deeper into the soil under CC compared with NC management. Effectively, the current study shows that CC management can increase rapid water movement within the soil, and this can increase soil water storage and reduce surface ponding (on relatively flat surfaces) and runoff (on sloping surfaces).

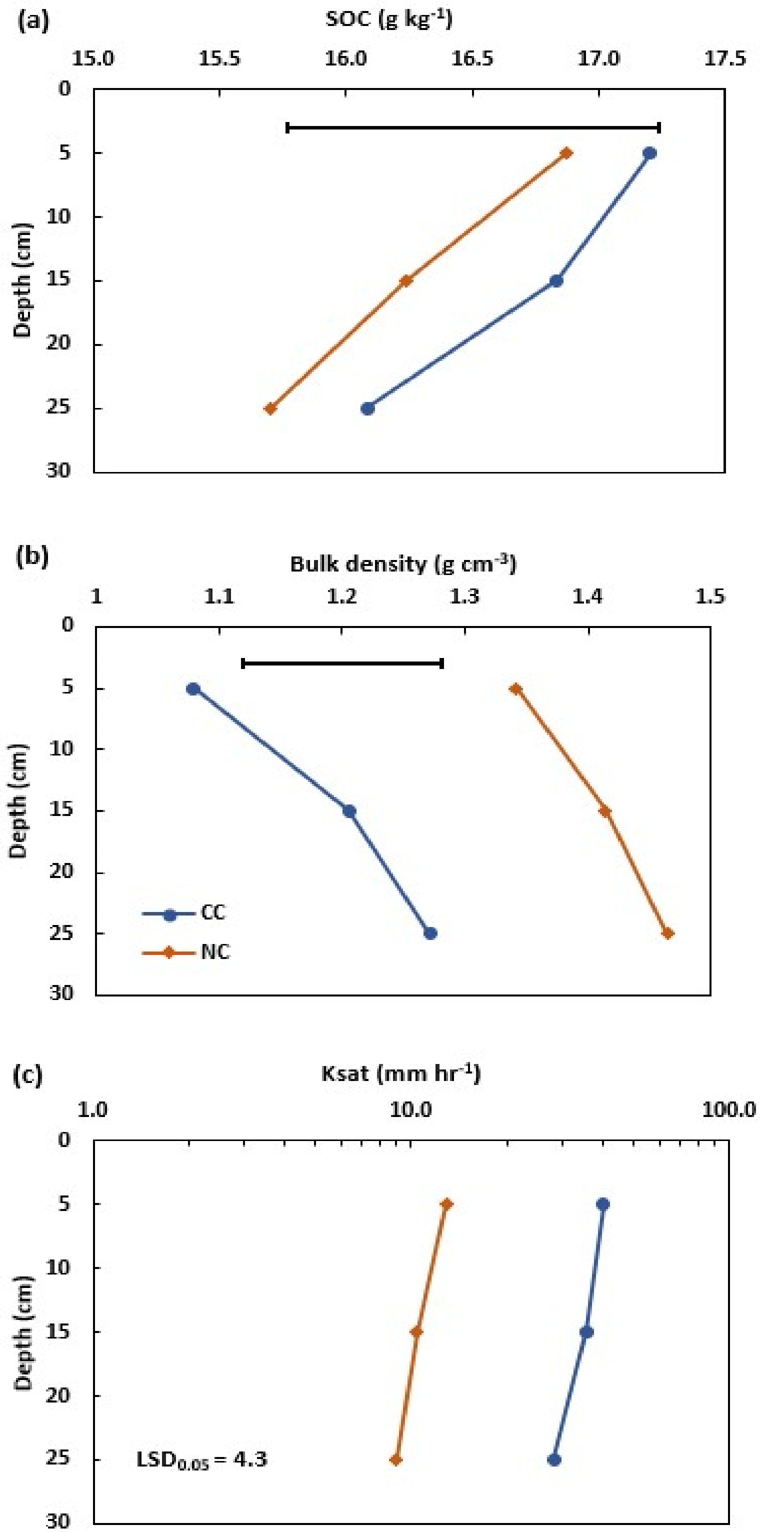


**Figure 2.** Soil properties relative to depth during the study period: (**a**) soil organic carbon (SOC), (**b**) soil bulk density, and (**c**) saturated hydraulic conductivity ($K_{sat}$). Bar represents LSD at 0.05. Due to log scale, the LSD value for $K_{sat}$ is provided rather than using a bar for the representation. Note: CC = cover crops, NC = no cover crop.

*3.2. In Situ Soil Water Potential*

The weekly means (with SE) and ANOVA for SWP under both management practices are shown in Table S1. Additionally, the weekly averaged SWP at each depth are shown in

Figure 3. The treatment X depth interaction results showed that CCs generally resulted in a lower SWP for all depths throughout most of the study period when compared with NC treatment (Figure 3). Overall, the range of SWP for the CC treatment was −26.89 kPa to −1.17 kPa, while the range under NC management was −22.31 kPa to −0.35 kPa.

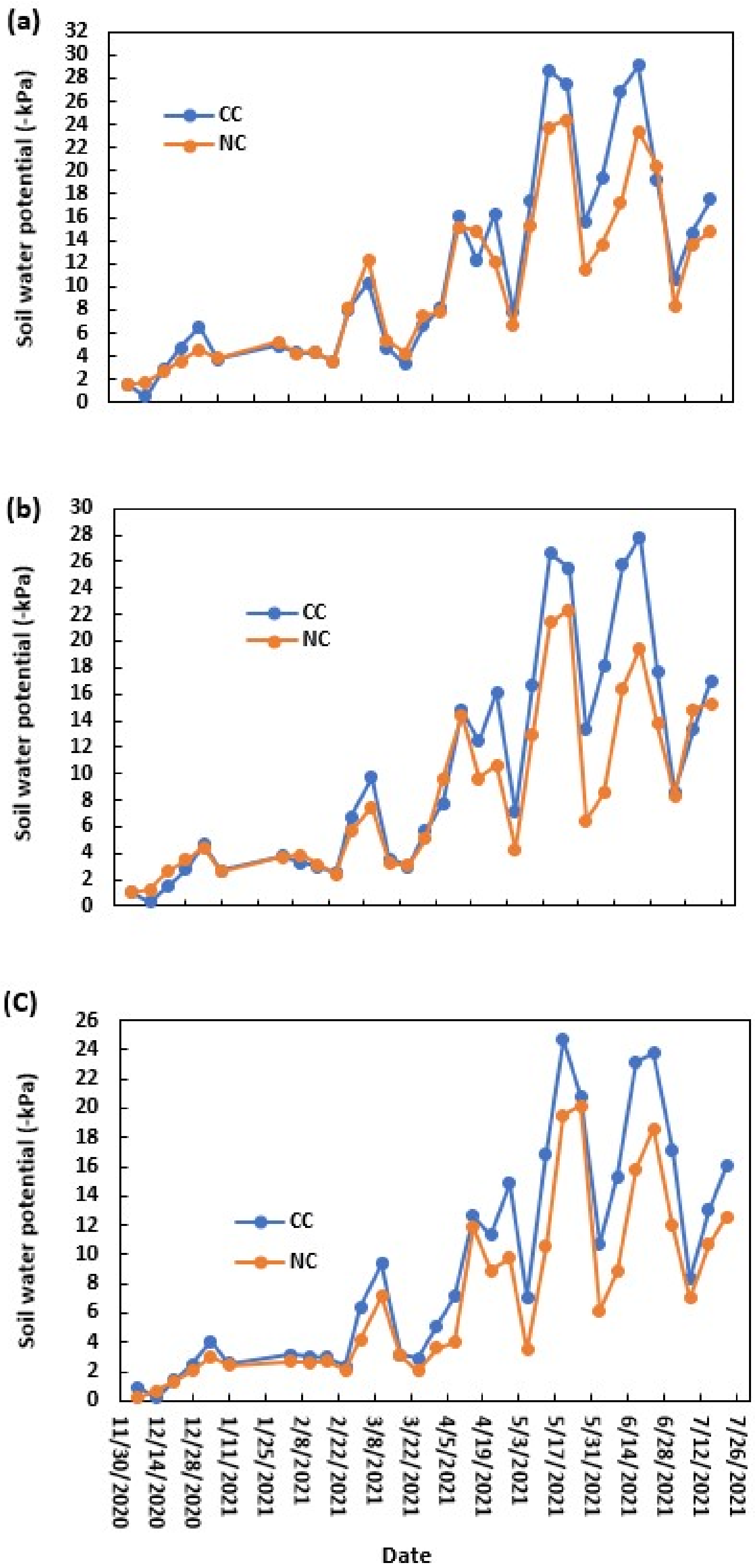


**Figure 3.** In situ-measured soil water potential at (**a**) 5 cm, (**b**) 15 cm, and (**c**) 25 cm at the research site. All dates are in the MM/DD/YYYY format.

Averaged over all depths, the first 2 months of measurements did not show any significant differences in SWP between CC and NC managements, apart from the weeks of 14 December 2020 and 4 January 2021 (Table S1). During these weeks (14 December 2020 and 4 January 2021), CC management significantly lowered SWP compared with NC management. Although not significant, CC had numerically lower SWP compared with NC management during the rest of the first 3 months of measurement. This was attributed to emerging CC activities (CCs were planted in October). Plant growth and development requires cell turgor pressure maintenance, and this is achieved by keeping a lower internal potential than the external SWP [38]. Coupled with the precipitation during this period (Figure 1), the emerging CCs need to therefore transpire water in order to maintain their cell turgor pressure. Consequently, a pressure differential occurs between the plant cell and soil, resulting in water movement from the soil into the plant cell (water absorption). As this process continues, the SWP will eventually become lower under CC compared with NC management.

During February, when the ambient temperature was lowest (Figure 1), there was no significant difference in the depth-averaged SWP between CC and NC managements (Table S1). This was probably due to the CCs going dormant during this period. However, as the atmosphere and soil warmed up during March and April, CC growth resumed, leading to more water use (transpiration) and, eventually, significantly lower SWP under CC compared with NC management during this period (Table S1). This agrees with [15], who reported lower soil water content due to high transpirative demand just before mowing.

The current study therefore shows that CCs can transpire excessive water from the field, and this can be beneficial during wet seasons as it can lengthen the growing season [39]. Further, lower water content (antecedent water content) can increase water infiltration [32], leading to higher saturated flow and storage, which agrees with the $K_{sat}$ results. Results also showed that water loss from CC transpiration is greater than evaporation water loss, suggesting that CCs can improve evapotranspirational efficiency under the right climatic conditions.

Interestingly, after CC termination during the week of April 22, CC management resulted in significantly lower SWP compared with NC management throughout the remainder of the study period (except the week of July 15) (Figure 3; Table S1), and this disproved the hypothesis of this study. This could probably be due to the improved soil health parameters (lower bulk density, improved Ksat, and SOC) creating a suitable environment for plant growth. The potentially healthier crops under CC management are likely to use more water from the soil compared with NC management. This is consistent with Figure 3, which shows that SWP between treatments start to diverge around the time the cash crops started growing. Unfortunately, crop biomass was not measured during the growing season in the current study, which could have provided reliable support to the explanation presented here.

Conversely, when the authors of ref. [40] conducted a study on the effects of soil matric potential on root growth of radiata pine (*Pinus radiata* D. Don) seedlings, they reported that root elongation rate decreased proportionally with decreasing soil potentials between −10 kPa and −350 kPa. However, research has shown that −30 kPa SWP at 30 cm depth is the irrigation threshold for corn in a similarly textured soil [41]. Since neither CC nor NC management reached this level, it seems unlikely that the subsequent corn cash crop will undergo significant water stress. However, this may not be true for a different cash crop, or during drier years, or in arid and semiarid regions.

As expected, SWP was significantly lower at the 0–10 cm depth and increased with increasing soil depth throughout the study (Figure 3; Table S1). This was attributed to (1) differences in the proportion of soil particles (lower clay content 10 cm below the soil surface; Table 1), (2) greater water transpiration under CC management (since plant root density decreases with increasing soil depth [42]), and (3) greater water evaporation under NC management (since the surface soils are exposed to solar radiation and higher daily and seasonal temperature amplitude).

In order to understand the effects of measured soil properties (clay, BD, Ksat, and SOC) on SWP, a regression analysis was conducted at each measured soil depth. Clay-sized particles were used as proxy for soil texture due to their higher surface area per unit volume and higher water retention abilities. The equations that provided the best estimate for SWP at each depth are provided below:

At 0–10 cm depth,

$$SWP = -36.396 + 2.497clay - 24.935BD - 0.426Ksat + 2.872SOC \ (r^2 = 0.84) \quad (1)$$

At 10–20 cm depth,

$$SWP = -32.596 + 0.785clay - 15.982BD - 0.243Ksat + 0.028SOC \ (r^2 = 0.99) \quad (2)$$

At 20–30 cm depth,

$$SWP = -31.229 + 1.608clay - 1.856BD - 0.031Ksat + 0.724SOC \ (r^2 = 0.85) \quad (3)$$

Although the models were not significant at all depths measured, SOC was the most important variable that influenced SWP at the 0–10 cm soil depth. Therefore, water availability for plant uptake is likely to depend on residue availability at the top 10 cm of this soil. As such, if CC residues are returned to the soil surface, they may have a significant effect on soil water availability (Table S1). At the 10–20 and 20–30 cm depths, clay content had the greatest influence on SWP. This was probably due to the clayey content of the soils, which are responsible for most of the capillary pores that determine soil water energy beyond saturation. Therefore, estimation of plant available water and irrigation schedule on soils similar to those in the current study should be partly based on soil clay content, especially at the deeper soil depths.

One of the reported benefits of CCs is their ability to conserve soil water, especially while they are actively growing [12,43]. Results from the current study seem to show that this benefit can extend beyond their termination and can result in improved water uptake. However, this was only true for a particular cash crop (corn) in a sub-humid climate and could be different in drier regions of the world, and also in resource-limited regions where most agricultural practices are rain-fed. Therefore, effective planning for CC implementation is important, particularly with termination timing and in concert with climatic conditions in order to generate positive agronomic benefits.

## 4. Conclusions

This study measured the impact of cover crops on various soil properties prior to their termination, as well as on soil water potential both before and after termination. Results showed that CCs numerically increased SOC and significantly increased $K_{sat}$ but lowered BD due to their biomass and root activity compared with NC management. Additionally, CCs lowered the SWP compared to NC, as the transpirational requirements of the plants outweighed the evaporative forces on the NC plots. While this can lead to better infiltration in the CC plots, it is important to terminate CCs in a timely manner to avoid interference with the growth and development of the subsequent cash crop. Therefore, effective planning is needed with CC management in order to negate water stress for the subsequent cash crop.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14112549/s1, Table S1: Means (±SE) and ANOVA of in situ measured soil water potential at the study site.

**Author Contributions:** Data collection and analysis were conducted, and the first draft of the manuscript written, by author O.M.P. The study conception, design, and review of the first draft of the manuscript were conducted by author S.I.H. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The dataset generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

BD: bulk density; CC, cover crop; $K_{sat}$, saturated hydraulic conductivity; NC, no cover crop; SOC, soil organic carbon; SWP, soil water potential.

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